11.1 GUIDELINES FOR IMPLEMENTING MASS WASTING PRESCRIPTIONS

Hazards to Private Resources

The Acme Watershed Administrative Unit (WAU) contains many private residences and structures. Some of these private structures are located on naturally hazardous landforms, including debris flow fans, alluvial fans, stream terraces and on areas directly below steep hillslopes prone to failure. Some, but not all, of these naturally hazardous landforms have been identified and mapped by Whatcom County Planning Department (1992). This watershed analysis does not attempt to map all of the hillslope and fan hazard areas in greater detail. Nor does it attempt to map hazard areas in relation to private structures, since the number and location of such structures occurring on naturally hazardous areas will change over time. Therefore, we recommend that potentially hazardous land forms, such as debris flow and alluvial fans, streamside areas and areas below steep hillslopes, be identified during preparation for specific forest practice activities, although the Acme watershed analysis and the Whatcom County alluvial fan hazard maps can be used as general guides.

Impacts to private property, as opposed to public resources, are not formally considered in watershed analysis (WFPB, 1994), which means that vulnerability of private property to identified hillslope hazards is not determined, and rule calls with respect to private property are not developed because they are not public resources. However, the team conducting the Acme watershed analysis considered impacts to private property and recommends that mass wasting prescriptions developed for high and moderate mass wasting map units be applied on a voluntary basis in those areas of the Acme WAU where there is an absence of fish-bearing channels but that contain private property vulnerable to mass wasting.

Map Resolution Issues

The slope stability assessment contained in watershed analysis is based on up-to-date scientific information on landsliding and the effects of forestry activities on landslide initiation, and therefore, forestry-related landsliding is expected to be substantially reduced when potentially-unstable landforms are identified in the field and prescriptions are followed. However, in some cases, areas of potential landslide hazard may not have been identified accurately during a watershed analysis (or any slope stability assessment) because of: 1) the dependence on remote-sensed data (i.e. aerial photographs); 2) the relatively short (40yr) and unique history of storms that triggered the landslides used to create the mass wasting map units (e.g. longer and different time periods and larger storms than what occurred during the aerial photo record may yield landslides in areas previously mapped as low landslide potential); and 3) the incomplete scientific understanding of all landslide mechanisms. For all of the above reasons, the mass wasting map units and hazard units developed during this watershed analysis may not completely identify all of the potentially unstable areas. In addition, because of the inherent difficulty in recognizing the exact combination of failure mechanisms at each site, the recommended prescriptions may not in every case reduce or eliminate forestry-related landsliding. Furthermore, naturally-occurring landsliding, that is not related in any way to forestry activities, can present a significant natural hazard to public (and private) resources, and these landslides cannot be predicted, nor at times can they be differentiated from landslides related to land use activities.

Implementation of prescriptions that apply to mass wasting hazards in the Acme WAU require the identification of mass wasting map unit (MWMU) boundaries in the field by the proponent. The identification and field verification of map unit boundaries shall be accomplished during preparation for forest practice activities by using the descriptions, based primarily on slope gradient, slope form, and evidence of past landslides which are listed in Table 3-2 of the mass wasting module. As part of the forest practice application, the applicant shall clearly identify the locations of ARS MW-1, ARS MW-2, and ARS MW-3 or state that none of the above were found in the proposed forest practice. A detailed forest practice preparation narrative shall accompany Forest practice applications that implement prescriptions applicable to mass wasting hazards. The narrative shall explain decisions made in cases where prescriptions offer flexibility, such as in the cases of wind throw prevention measures and bedrock hollow crossing structures.

Specialist Qualifications

To qualify as a **geotechnical specialist**, an individual should have specialized education and field experience related to the affects of forestry activities on slope stability in the Pacific Northwest. At a minimum, the specialist should have university-level training in slope stability or hillslope geomorphology, and five years experience in assessing slope stability in forested mountain areas involving forest practices. An advanced degree in geomorphology emphasizing hillslope processes, including all forms of slope instability, is preferred.

To qualify as a **forest engineer** for the purposes of advising on road construction prescriptions, an individual should have a minimum of five years of appropriate field experience and either a bachelor of science degree in forest engineering or specialized education related to the location, design and construction of roads in mountainous terrain.

11.2 CAUSAL MECHANISM AND PRESCRIPTION REPORTS

Acme WAU
Report #1

Resource Sensitivity:	ARS MW-1
Input Variables:	Debris flow scour and deposition; channel aggradation; coarse and fine sediment (and woody debris)
Hazard:	Moderate or High
Vulnerability:	High (Fish habitat) High (Public Works)
Rule Call:	Prevent or avoid

Situation Statement:

Debris flows and dam-break floods from MWMU #1, MWMU #2, MWMU #3, MWMU #4, MWMU #5, MWMU #7, and MWMU #10 have the potential to deliver large volumes of coarse and fine sediment to water and fish habitat in Channel Segments #5 and #6. Coarse sediment deposition could also impact public bridges and adjacent roadways (Bridges #7 through Bridge #13, and Bridge #17 on the Public Works map). Debris flow deposits could bury channel roughness elements (boulders, LWD) and fill pools. Loss of these channel obstructions could increase average water velocities, reduce new pool formation rates, and reduce localized storage of spawning gravels. Aggraded channels allow greater sub-surface flow, which would extend periods of dry channels during low flow seasons. Fine sediments (<0.85mm) have the potential to degrade rearing and spawning habitat in Channel Segments #1, #4, #5, and #6 by filling pools and reducing spawning gravel suitability. Suspended sediment can also affect fish when delivered in sufficient quantity and duration.

Map Unit Description and Process

Please refer to the Mass Wasting Assessment for more detailed description and discussion of these MWMUs.

MWMU #1 and MWMU #4 are convergent topography greater than or equal to 36 degrees (73%), and include bedrock hollows, channel heads, AND inner gorges (see landform definitions) of first-order channels. These map units are naturally prone to landsliding, and are the primary source of debris flows. To see field examples of bedrock hollows, refer to photographs in: *Slope Instability and Forest Land Management, A Primer and Field Guide*, 1997/1998, Benda, L., Veldhuisen, C., Miller, D., Miller, L., Earth Systems Institute, Seattle, WA, 84 pages (see Appendix).

MWMU #2 and MWMU #5 are inner gorges, greater than or equal to 40 degrees (84%) in Chuckanut Formation or greater than or equal to 36 degrees (73%) in phyllite terrain, along second- and higher- order channels which contain all slope forms (convergent, divergent and planar). Landslides in these map units may trigger debris flows or dam-break floods.

MWMU #3 is generally non-convergent topography, greater than or equal to 31 degree (60%) hillslopes with primarily thin soils (3 to 6 feet). Bedrock hollows can occur here in various forms of development. The oldest features are deeply incised with sideslope gradients typically in excess of 45 to 50 degrees. In these cases, the drainage divide of a mature hollow may be 500 to 7—feet from the hollow axis (for photo examples of bedrock hollows, see Benda et al (1998)). Note that the actual drainage divide of a hollow is likely a subtle break in slope as the hollow slowly breaks into a planar or divergent surface. These strongly convergent and steep hollows are the most potentially unstable.

Hollows in earlier phases of development (i.e., younger) also exist in the Acme WAU and are characterized by more subtle convergence with slide slope gradients ranging from 30 to 40 degrees (the hollow axis may also be less steep). The drainage area of these hollows (also referred to as "wedges" by Buchanan (1998)) can be relatively small, and the drainage divide of small hollows may extend less than 100 to 200 feet away from the hollow axis. These sites are less potentially unstable since they should have a lower convergence of soil and groundwater. It is possible that small hollows that are filled with soil will be difficult to detect in the field. Likely locations of small hollows are at the heads of first-order or type 5 streams.

Although the relative stability is greater than MWMU #1, #2, #4 and #5, MWMU #3 also contains inclusions of convergent topography greater than or equal to 31 degrees (60%), including inclusions of MWMU #1.

MWMU #7 is an undifferentiated mixture of MWMUs #1, #2, #3, #4, and #5, as well as stable topography. MWMU #7 can also contain areas described by MWMU #6 (Devil's Slide), although the approximate perimeter of the Devil's Slide area is demarcated by MWMU #6 in Figure 3-3.

MWMU #10 is generally planar topography, 31 to, but not including, 36 degree hillslopes with primarily thick soils adjacent to inner gorges in phyllite terrain which contains all slope forms (convergent, divergent and planar). Although the relative stability is greater than MWMU #1 and MWMU #2, landslides in this map unit may trigger debris flows or dam-break floods. Landsliding mechanisms include shallow and small (<200 square feet) deep failures, including earthflows.

<u>Landform Definitions</u>

Some *signs of instability* that could be used to define MWMU #1, MWMU #2, MWMU #3, MWMU #4, MWMU #5 and MWMU #10 include:

i) existing landslides and old landslide scarps;
ii) discontinuity surfaces as described in the Mass Wasting

Assessment pg 3-19 (Buchanan, P. 1988, Debris avalanche and debris torrent initiation, Whatcom County, Washington, U.S.A. MS thesis, Department of Geological Sciences, University of British Columbia);
iii) tension cracks*;
iv) scarp and bench topography indicating rotational slumps*;
v) tipped and jackstrawed trees*;
vi) springs and hydric vegetation.
(* more indicative of deep-seated failure sites, rather than shallow-rapid landslide sites)

A *channel head* is generally located in a convergent area, often at the base of one or more hollows, where subsurface flow emerges and a channel, defined by banks and substrate, begins.

A *high-hazard bedrock hollow* is defined as an unchanneled swale or valley with a slope gradient downhill along the axis of the hollow greater than or equal to 36 degrees (73%). Hollows may also contain the channel head; an area often characterized by springs and small landslide scars, where a channel is first identifiable. The more convergent the hollow the higher the likelihood of failure. Swales with no soil because of recent failure may present minimal hazard. The unstable portion of the hollow scales with the size of the landform. Small (narrow) landslides may occur in small narrow hollows along inner gorges. Wider landslides may be more representative in broader hollows on high relief hillslopes. Field measurements and aerial photographs indicate that the potentially unstable portion of hollows on high-relief hillslopes (see Mass Wasting Assessment) may range from 4 to 40m wide centered around the hollow axis, and the distance from ridgetops to the tops of landslide scars may range between 20 and 260m (average= 60m) and the potentially unstable portion may encompass the bottom 75% of the hollow length. Field surveys revealed landslide within hollows that ranged from 4 m (13 ft) to 12 m (40 ft) and averaged 7 m (23 ft). The potentially unstable zone of any hollow, therefore, needs to be determined in the field based on these guidelines, the size of the hollow and landform, and the signs of instability outlined above (i.e. "i - vi"); also see the guidelines in Benda, et al., 1998 (Appendix 1). The width of the zone shall be expanded by a minimum of 15 feet on either side to account for tree roots intersecting the failure plane and shall extend from the bottom to at least 75% of the entire length of the hollow. The zone shall be further extended to encompass those areas exhibiting significant signs of instability (see below).

As a voluntary alternative to extrapolating landslide site location from one hollow to another based on limited field data, a computer model could be used to predict the location of the most unstable zone (e.g. potential landslide site) in any bedrock hollow (i.e. distance down from the ridgetop and the width of the slide). Careful application of such a model may allow more accurate and defensible siting of buffer strips. Model development would need to account for: 1) mechanics of shallow failure including soil mechanical properties; 2) root strength (vertical and lateral) controlled by forest stand age and linked to the geometry of the landslide scar; and

3) subsurface flow linked to hollow geometry and local precipitation data. The model would be applied on a site specific basis; supporting data should include: 1) longitudinal profile of the hollow; 2) along-contour profiles to determine hollow geometry, including relief; 3) soil depths along the hollow axis; 4) along axis and side slope (or convergence) gradients; and 5) vegetation age.

A *moderate-hazard bedrock hollow* is defined as an unchanneled swale or valley with a slope gradient ranging from 31 to, but not including, 36 degrees downhill along the axis of the hollow. The more convergent the hollow the higher the likelihood of failure. Swales with no soil because of recent failure may present minimal hazard. Identifying the potentially unstable portion of a moderate hazard bedrock hollow should follow the same guidelines described for high hazard bedrock hollows.

An *inner gorge* is defined as the valley floor and hillslopes adjacent to a stream channel where hillslopes, with the following gradients, extend a minimum relief of 5 meters (16 feet) above the channel:

First-order streams (stream gradients generally in excess of 20%)

All Terrains — Hillslope gradient ≥36 degrees (73%)

Second- and higher order streams (stream gradients generally < 20%)

Chuckanut Formation — Hillslope gradient ≥40 degrees (84%)

The minimum 40-degree inner gorge slope gradient was determined from field surveys of inner gorge landslides in the sandstone formation of the Acme WAU.

Phyllite Terrain — Hillslope gradient ≥36 degrees (73%)

Field evidence of shallow landsliding, small rotational slumps, tension cracks, and tipped and deformed trees should be used to refine gradient breaks on a case-by-case basis. In the absence of evidence of landsliding, the 36 degree cutoff should be applied.

Slope gradients should be measured at the scale of small landslides (i.e. tens of meters). Only planar and divergent slope forms are covered in these hillslope gradient classes. The hillslope gradient cutoff does not include bedrock hollows located in inner gorges. Bedrock hollows located in inner gorges are defined by the slope gradients previously described for MWMU #1, #2, #3, #4, and #5. When landslides are observed on planar or divergent slope forms on hillslopes adjacent to streams, the slope gradient of the landslide head scarp should be used to define nearby hillslope gradients that are at risk from landsliding.

Triggering Mechanism(s):

Timber harvest reduces rooting strength in the soil and thereby can increase landslide frequency for approximately 5 to 20 years following harvest. A secondary effect of canopy removal is increased moisture inputs during rain-on-snow conditions, which can increase local soil moisture and contribute to slope failure. Failure of road fills may trigger landslides and debris flows. Water concentrated by road drainage can increase pore water pressures thereby decreasing slope stability. In the absence of forest practice activities, heavy precipitation or rain-on-snow events alone may trigger landslides and debris flows in any of the MWMUs. Although most slope failures appear to be associated with roads, it was not possible to determine the relative importance of these individual factors in triggering landslides since most inventoried landslides are old, road failures have been repaired, and remote sensing was the primary tool used during the watershed analysis. However, site-specific assessments of landslide prone areas may identify the relative importance of these factors to improve understanding of triggering mechanisms. In some instances windthrow has initiated shallow-rapid landslides. Timber harvest triggering mechanisms do not apply to MWMU #10.

Prescriptions:

- New Road Construction

  Proposed new road construction shall, in most instances, select alternatives that avoid MWMU #1, MWMU #2, MWMU #3, MWMU #4, MWMU #5, and MWMU #10. In rare instances, a well-engineered road may provide greater environmental protection than other alternatives (e.g. one crossing rather than multiple switchback roads up parallel ridges). In such cases, the DNR may permit road construction if the landowner can demonstrate that a full range of alternatives have been considered and that the chosen alternative is not expected to increase the likelihood of mass wasting or contribute to the magnitude of a potential failure. Such roads would preferably be of a temporary nature, but it is recognized that permanent access for management activities will be necessary on some primary road systems.

  If roads are constructed within these mass wasting units:

    A. Stream and hollow crossing structures (e.g. bridges, culverts, fords) shall utilize keyed rock fills and be designed by a qualified forest engineer for a 100-year peakflow event. Fills shall be dipped to allow passage of upslope failures. Dipped fills or fords shall be surfaced with non-erodible materials such as hard rock, concrete, or asphalt.

    B. All road and stream-crossing structures within inner gorges shall be designed, slope-staked, and field referenced by a qualified forest engineer. In addition, all road construction shall be supervised on site by a forest engineer. Road lengths and widths within the mass wasting unit should be minimized to the extent that they remain compatible with safety requirements regarding the movement of logging trucks and yarding equipment.

C. All design drawings shall be included with the Forest Practice Application.

D. Full bench end haul construction shall be required within these mass wasting units.

E. Road drainage shall be designed to minimize water accumulation in ditches and prevent diversion between sub-drainages. This requires immediate passage (culvert, ford, or waterbar) at all drainages crossed by the road, including ephemeral channels and seeps. In addition, frequent cross drainage shall be installed at suitable locations to drain water accumulations from ditches. Suitable cross-drain locations feature a stable cut-slope and drain onto ridges or other stable slopes. Outfalls shall not be located in inner gorges unless consistent with natural drainage patterns.

F. Fine-scale secondary slope stability assessment by a qualified geotechnical specialist is required. The assessment should follow the approach and methods outlined in the most current version of the mass wasting module and should answer, at a minimum, the following questions: Will water be diverted into the MWMU? Will the hillslopes above or below the road be destabilized? Will the road fills be stable?

G. Crossing and drainage structures, as well as associated stabilization measures must, be completed before moving construction equipment from the site.

H. Construction will occur only during periods of suitable weather conditions, typically from May 15 to October 15.

- Orphaned Roads

For the purposes of these prescriptions, orphaned roads are defined as roads constructed prior to and unused for forest practice activities since the effective date of the Forest Practices Act of 1974. Landowners shall review all orphaned roads lying within the harvest unit or within 500 feet, either upslope or downslope, of any proposed timber harvest or road construction activity. Concurrent with Forest Practice activity, instability problems shall be remediated, if practicable, on any orphaned road segment which is delivering or has the potential to deliver significant coarse sediment (i.e. mass failures or active gullying) to streams or to roads (proposed or existing).

- Timber Harvest

General

Evaluation of the hazard and impact of windthrow on inner gorge and high-hazard bedrock hollow leave areas shall consider comments and references presented in the appended project report, Evaluation of fall 1998 windthrow in slope stability leave areas at the Jones Creek and Hardscrabble harvest units (Veldhuisen, 1999). Appropriate management strategies shall be employed wherever, in the opinion of DNR, windthrow would substantially reduce the function of the leave area.

At times, harvest boundaries may be located along an abrupt edge demarcating an inner gorge or a high-hazard bedrock hollow. Trees located along the edge (i.e. straddling the boundary) may be contributing some lateral root strength. If there are numerous mature trees below the edge, then trees along the boundary may not be necessary to provide root strength. The removal of a portion of the trees overlapping the boundary may be allowed, where in the opinion of DNR, removal does not significantly reduce the rooting strength of the entire potentially unstable feature. Edge trees should not be harvested if there exist tension cracks or unvegetated landslide scars immediately below the boundary, or if there are very few trees on the unstable feature. The goal of this prescription is to provide relatively even distribution of leave trees on the edge of the unstable feature.

Inner Gorges of first order streams

No harvest within 75 feet slope distance of the high-water mark of the stream or to the first break in slope less than 36 degrees (73%), whichever is least. No inner gorge trees shall be used as tail-holds.

Minimal tree removal may be permitted to provide corridors for full-suspension skyline yarding provided that:

A. Skyline yarding would avoid otherwise necessary road construction, particularly when the only road access option would require road construction across these mass wasting units.

B. Corridor placement results in minimal cutting of trees.

C. Location of corridors shall be free of significant signs of instability.

D. Falling and yarding operations shall result in minimal soil disturbance.

E. Total corridor area shall not exceed 15% of the riparian area in the harvest unit.

Inner Gorges of second- and higher order streams

Harvesting shall not occur within inner gorges. No inner gorge trees shall be used as tail-holds. Minimal tree removal may be permitted to provide corridors for full-suspension skyline yarding according to conditions noted above.

High-Hazard Bedrock Hollows

Harvesting shall not occur in the potentially unstable zone (see landform definitions) of high-hazard bedrock hollows where landslides are predicted to reach streams (See appended project report Method to Predict Landslide Runout on Non-Convergent Hillslopes by Lee Benda, Ph.D.) No trees within these unstable portions shall be used as tail-holds.

Steep Slopes Outside of Inner Gorges and High-Hazard Bedrock Hollows

No harvesting on slopes greater than or equal to 36 degrees where significant signs of instability exist and landslides are predicted to reach water or fish habitat. (See appended project report Method to Predict Landslide Runout on Non-Convergent Hillslopes by Lee Benda, Ph.D.)

Technical Rationale:

The ability of landslide debris to enter stream channels depends on their runout characteristics. Although there are published runout models for channelized debris flows, there are no published models for landslide debris movement on non-channelized (planar) slopes. To circumvent this problem, a runout model was developed in the Acme watershed analysis by Dr. Lee Benda, based on the theoretical principle and empirical finding that landslide debris, which contains a relatively rigid (non-shearing)plug on the surface, will spread and thin, and deposit. A landslide runout model was developed based on this concept using published equations for shear stress of landslide debris and empirical data on runout geometry from the Acme WAU.

The landslide runout model for non-convergent hillslopes is currently being tested using data from the Oregon Dept. of Forestry. The model, however, should be used cautiously since it has not been rigorously tested. The model should be used in conjunction with other field indicators of instability and topography by experienced field practitioners. The accuracy of the model should be periodically evaluated by comparing model predictions with actual runout distances of landslides on non-convergent hillslopes.

The prescriptions are designed to prevent road failure hazards (e.g. fill failure, water concentration) during the winter storm season. Site-specific review and analysis are intended to identify which engineering techniques address and mitigate causal mechanisms.

Harvesting prescriptions are designed primarily to maintain an effective level of rooting strength and secondarily to avoid increased moisture inputs during rain-on-snow and soil disturbance from harvest activities within unstable areas.

Most landslides identified in the mass wasting module occur in bedrock hollows. The greatest number (72) of landslides occurred in high-hazard bedrock hollows (>=36°), but a relatively large number (54) also occurred in moderate-hazard bedrock hollows (31-35°). However, field study has indicated that approximately 90% of randomly selected bedrock hollows that had failed in clearcuts had slopes >=36°. Based on that field work, we chose to apply road prescriptions to both types of bedrock hollows and to apply harvesting prescriptions to high-hazard bedrock hollows only, effectively addressing over 90% of all potential hollow landslide sites. Moderate-hazard bedrock hollows, with significant signs of instability and with potential delivery to streams, will be rare occurrences and are not addressed with harvesting prescriptions. However, this lack of prescription allows further conditioning under standard rules (WAC 222-22-010 (4) and WAC 222-22-090 (1d)) for moderate-hazard bedrock hollows where warranted by field evidence.

Although significantly fewer landslides (2) were recorded for planar slopes, the mass wasting assessment assigns a moderate hazard rating for 31 to 35 degree planar slopes (MWMU #3B) and a high hazard rating for greater than or equal to 36 degree planar slopes (MWMU #3A). In light of low failure frequency we have chosen to allow conventional harvesting techniques in MWMU #3B and have applied a no harvest prescription to portions of MWMU #3A with potential delivery.

Additional field assessment (See appended project report Acme WAU: Inner Gorge Topography, Landslide Inventory, and Management Practices by Lee Benda, Ph.D.) was conducted to better define landslide prone sites located within inner gorges in Chuckanut Formation. All 26 of the inventoried landslides occurred on slopes ranging greater than or equal to 40 degrees (84%). 75% of the slides occurred in hollows with the remaining 25% located on planar slopes. On the basis of this data, prescriptions prohibit harvesting on steep inner gorge slopes of any form (>=40 °).

These prescriptions are expected to reduce potential impacts to fisheries resources and water quality by reducing fine and coarse sediment inputs from mass wasting and limiting riparian disturbance (which contributes to temperature problems) caused by landslides and/or channel aggradation.

Mass wasting issues associated with existing roads will be dealt with according to road maintenance plans required by Washington State DNR under WAC 222-24-050.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #2

Resource Sensitivity:	ARS MW-2
Input Variables:	Primarily rockfall, possibly debris flows
Hazard:	High (with respect to road construction that alters the distribution of surficial bedrock) Low (for timber harvesting alone)
Vulnerability:	High (Fish habitat)
Rule Call:	Prevent or avoid

Situation Statement:

Rock avalanches from MWMU #6 have the potential to deliver large volumes of coarse sediment to water and fish habitat in Channel Segments #5 and #6. Sediment deposits could bury channel roughness elements (boulders, LWD) and fill pools. Loss of channel obstructions could increase average water velocities, impede pool formation, and lessen localized storage of spawning gravels. Aggraded channels allow greater sub-surface flow which would extend periods of dry channels during low flow seasons.

Map Unit Description and Process

MWMU #6 is the Devil's Slide area which contains relatively large-scale fracturing of bedrock with bedrock slabs gradually (or rapidly) moving downslope to the base of the ridge. This type of failure apparently arises because of large topographic stresses in combination with weak rock or by faulting. The role of groundwater (and therefore vegetation) appears to be minimal since the failure begins at the ridgetop and the failure is occurring in bedrock. Hence, timber harvest probably would not increase probability of bedrock slab failure. Road construction, however, that removes bedrock thereby changing the distribution of the rock mass or that significantly concentrates shallow groundwater flows along failure zones may contribute to bedrock slab failures.

Areas within MWMU #6 may contain shallow failures and landforms of the type described in MWMUs #1, #2, #3, #4 and #5. Since MWMU #6 is underlain by MWMU #7, these other types of slope failures (and landforms) are included in MWMU #7 and are discussed in Causal Mechanism and Prescription Report #1.

Triggering Mechanism(s):

Timber harvest probably does not play a role, although road construction that removes bedrock or significantly concentrates runoff may increase the probability of failures. Topographically-induced stresses in conjunction with weak sandstone bedrock is the predominant triggering mechanism, although faulting may also be important.

Prescriptions:

No new roads which require bedrock removal are to be built through MWMU #6. Road drainage patterns shall ensure that significant concentrations of ditch flows do not occur.

Technical Rationale:

The prescriptions are designed to avoid changing the surficial distribution of bedrock and the distribution of hillslope water.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #3

Resource Sensitivity:	ARS MW-3
Input Variables:	Coarse and fine sediment
Hazard:	High (for road construction and blasting)
	Moderate (for timber harvesting alone)
Vulnerability:	High (Fish habitat)
Rule Call:	Prevent or avoid

Situation Statement:

Deep-seated and shallow landslides, debris flows, and dam-break floods from MWMU #9 have the potential to deliver large volumes of coarse and fine sediment to water and fish habitat in Channel Segments #5 and #6. Mass wasting deposits could bury channel roughness elements (boulders, LWD) and fill pools. Loss of channel obstructions could increase average water velocities, impede pool formation, and lessen localized storage of spawning gravels. Aggraded channels allow greater sub-surface flow which would extend periods of dry channels during low flow seasons. Fine sediments (<0.85mm) have the potential to degrade rearing and spawning habitat in Channel Segments #1, #4, #5, and #6 by filling pools and reducing spawning gravel suitability. Suspended sediment can also affect fish when delivered in sufficient quantity and duration. Delivery of coarse and fine sediment onto the alluvial fan may pose hazard to structures and public works.

Map Unit Description and Process

MWMU #9 are large (>200 square feet), deep-seated landslides contained mostly within highly weathered phyllite bedrock but are found in Chuckanut Formation as well. The boundaries of the landslide are only approximately mapped. There are smaller, rotational slides within the main body of the slide mass which have the most potential instability, particularly when material is removed from the toes (of the smaller areas of instability). Sediment delivery should be minimal unless failures are immediately adjacent to stream channels. However, it is possible that deep-seated landslides located away from the channel can deliver sediment; this situation should be determined in the field.

Triggering Mechanism(s):

The triggering mechanisms for these slides are not well understood, since the large scale feature is mostly dormant. Recent harvest activity has occurred on portions of these slides, but insufficient time has passed for evaluation of the effects of harvesting. It is recommended that recent harvesting be assessed through periodic aerial photo analysis and field surveys to determine whether timber harvest or road construction contributes to failures.

Harvesting of trees on the active portion of a slide can reduce evapo-transpiration (ET) which may potentially lead to accelerated movement. In addition, harvesting of trees in the groundwater recharge zone (GRZ) can also potentially increase soil creep or failure rates (Miller and Sias, J. 1997). The effect of reduced ET on either the active slide area or in the GRZ in the Acme WAU is unknown at present. Hence, an approach is taken that focuses mitigation (no harvest or partial harvest) on the active portion of the slide area, with a lesser emphasis on the GRZ, until additional site specific information is available on the relationship between harvesting and landslide movement in the Acme WAU.

Similarly, new roads are more likely to contribute to movement when located on an active slide, due to drainage alteration and localized redistribution of soil masses. The primary concern regarding new roads within the GRZ and all existing roads is the potential for redistribution of water. Thus effective road drainage is critically important, especially during heavy rainfall events. Shallow landslides or debris flows initiated by roads on or above the deep-seated slide can have a serious destabilizing effect on deep-seated movement, as documented in the Warnick and Jordan/Boulder WAUs (1994 & 1996).

Prescriptions:

Operations within map unit #9 must be preceded by a thorough field inspection for deep-seated activity within the area of the proposed activities and downslope to Jones Creek. The purpose of the inspection is to locate active slumps (generally indicated by recent cracking, tipped trees, etc.) and determine whether delivery to streams is occurring or is likely to occur with further movement. The inspection can be performed by either a geotechnical specialist or forester.

If evidence of recent (within several decades) slide activity is found, the inspector must determine the extent of the groundwater recharge zone (GRZ) of the active slide area, by considering topography as one would to delineate a drainage basin for a stream. The topographic limit to the GRZ can be identified using one of the following methods, listed in order of most precise to least:

1. Walking the boundary on foot, using a clinometer.
2. Marking a boundary on aerial photographs, from stereo inspection.

Once the active deep-seated landslide and its GRZ have been delineated, activities are limited as follows:

- New Road Construction

  1. No new roads can be built through the active portion of a deep-seated failure.

2. For roads constructed within the GRZ, road drainage should be designed to minimize water accumulation in ditches and prevent diversion between sub-drainages. This requires immediate passage (culvert, ford, or waterbar) at all drainages crossed by the road, including ephemeral channels and seeps. In addition, frequent cross drainage shall be installed at suitable locations to drain water accumulations from ditches. Suitable cross-drain locations feature a stable cut-slope and drain onto ridges or other stable slopes. No additional water shall be diverted into the active slide area.

3. No road construction within the no-harvest buffers noted in the timber harvest prescriptions.

- Timber Harvest

No timber harvest in the active portion.

Timber harvest within the GRZ can occur under either of the following conditions:

1. Clearcut harvest operations must leave an uncut buffer along the upper margin of the active area, covering an area equivalent to 50% of the active portion.

2. Selective harvest operations must preserve a minimum relative density of 35 among residual stems greater than 25 years of age. Relative density is calculated by dividing the stand basal area per acre by the square root of the quadratic mean stand diameter at breast height.

3. Study by a geotechnical specialist indicates that slide activity did not increase following prior timber harvest and/or road construction. Such a study would require review of historical aerial photographs that would show slide conditions during the 30-year period following prior activities. The study should also involve a detailed site investigation of the area (e.g. the active or dormant landslide) to ascertain whether past harvest (or road construction) has led to failure. Field evidence would include new or old tension cracks that could be dated to the time of harvest or within 10 to 15 years after, split stumps, and displaced logging or spur roads. The conclusions of this secondary analysis must be supported by complete scientific justification and be capable of withstanding technical scrutiny.

<u>Technical Rationale</u>:

Without clear triggering mechanisms in the active deep-seated landslides in the Acme WAU, we cannot be certain of the effectiveness of any prescriptions. Therefore, we apply harvest restrictions based only on evidence of active deep-seated landslides. The harvest restrictions are intended to maintain evapo-transpiration by hydrologically mature timber on active deep-seated landslides and in a portion of the GRZ immediately above. Assuming that tree growth rates serve as a proxy for evapo-transpiration, the relative density minimum allows harvesting down to the lower level of the range in which maximum growth of pure Douglas fir stands occur.

These prescriptions are expected to contribute to improved water quality, by reducing fine sediment inputs from mass wasting and limiting riparian disturbance (which contributes to temperature problems) caused by landslides and/or aggradation.

Mass wasting issues associated with existing roads will be dealt with according to road maintenance plans required by Washington State DNR under WAC 222-24-050.

Monitoring Recommendation

In an effort to gain a better understanding of the factors which influence its movement, it is recommended that affected landowners adopt and implement a program for monitoring active deep-seated landslides, particularly when harvesting within the GRZ. Monitoring may include annual site inspections or use of aerial photographs during 5-year reviews of watershed analysis.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #4

Resource Sensitivity:	ARS SE-1
Input Variables:	Fine sediment from road surface erosion
Hazard:	Moderate or High
Vulnerability:	High (Fish habitat)
Rule Call:	Prevent or avoid

Situation Statement:

The N-1000 and other gravel roads in the Southeast sub-watershed produce substantial fine sediment, most of which is routed toward the Black Slough. Similarly, the many newly constructed roads in the Northwest and Southwest sub-watersheds contribute fine sediment to western tributaries (e.g. McCarty, Standard, Hardscrabble and Todd Creeks) and the South Fork Nooksack. Fine sediments (<0.85mm) have the potential to degrade spawning and rearing habitat by decreasing depth and volume of rearing habitat and reducing spawning gravel suitability. Suspended sediment can also affect fish when delivered in sufficient quantity and duration.

Triggering Mechanism(s):

SE Sub-watershed: Although many roads contribute, most sediment appears to originate from the primary haul road: N-1000. Most sediment is generated from the road surfaces due to hauling wear.

NW and SW Sub-watersheds: Most sediment is contributed from various recently-constructed (i.e. 1998 & 99) roads. Although much of the sediment is generated from the tread in response to hauling traffic, additional amounts come from recently exposed cutslopes.

Prescriptions:

- New Road Construction

  New roads should be located to avoid stream crossings if possible. Where stream crossings are necessary, the length of ditches draining directly to streams shall be limited to 200 feet or less. Some combination of grass seeding with native species, hydro-mulching, and sediment traps shall be utilized on direct entry segments to minimize erosion, at the time of construction.

- Existing Roads - Active and Inactive

Additional cross-drains shall be installed along existing roads to limit the length of all ditches draining directly to streams to 200 feet or less. These cross drains are due within 1 year of approval of this watershed analysis or in conjunction with Forest Practice activities, whichever comes first.

Sediment traps and/or settling ponds shall be used on direct entry segments when hauling during wet-weather.

Technical Rationale:

SE Sub-watershed: Because most surface erosion is generated from the N-1000 road, reducing direct entry will substantially reduce the total sediment delivery. Less traveled spur roads are only minor contributors. New roads could produce substantial surface erosion, especially for first 1-2 years following construction.

NW and SW Sub-watersheds: A substantial number of new forest roads were constructed in 1997 & '98. Roads were generally built to high standards in terms of tread surfacing, drainage design that minimizes ditch entry to streams and efforts to revegetate cutslopes via grass-seeding. Still erosion research suggests that sediment production rates are elevated over the first two years following construction, until exposed soils become armored. Because there are many new roads undergoing this "seasoning" process, the total sediment contribution slightly exceeds the background rate of sediment from soil creep, indicating potential turbidity impacts.

Several additional segments of road construction are projected for 1999 and 2000 to reach currently inaccessible parts of the WAU. Once these roads are completed, road construction rates are expected to drop off sharply. Total road sediment inputs should drop considerably as the many roads built between 1997-2000 pass the two-year age mark when the basic erosion rates drop to one-half the rate for 0-2 year-old roads. Depending on the future condition of the road network (traffic, revegetation, abandonment, etc.) at that time, total road sediment inputs are projected to stabilize at levels associated with Low or Moderate hazard ratings.

Technical Note:

Road surface sediment generated in the Southeast sub-watershed is much more likely to influence fish habitat in the Black Slough than the South Fork Nooksack. This is because the Black Slough is a very low-gradient stream that traps much of the fine sediment, reducing transport into the mainstem. Also, sediment input rates from the Southeast sub-watershed constitute a very small part of the total mainstem sediment load (<<1%), even on a per-unit-area basis. Of the fine sediment produced from roads in the Northwest and Southwest sub-watersheds, greater proportions are expected to reach the South Fork, due to steeper tributary gradients (compared to Black Slough) which allow more efficient transport. Still the contribution to the overall fine sediment load in the South Fork is relatively small, once compared to the large fine sediment volumes originating in the upper basin. However, the potential for sedimentation impacts in the relatively steep western tributaries is lower, compared to the Black Slough.

Voluntary Remedial Opportunity

Spur roads with ditches draining directly to streams should be abandoned and seeded with native grasses after harvest is complete.

Use of Central Tire Inflation (CTI) on logging trucks, if economically feasible, should be considered on all haul roads subject to surface erosion from truck traffic (See Moore, T., R.B. Foltz, and L. Cronenwett. 1995. Central tire inflation reduces sediment up to 84%: A method to help meet new water quality standards and guidelines. USDA Forest Service, Technology & Development Program, Tech Tips, San Dimas, California).

Resurfacing main haul routes with asphalt or with other non-erodible surfacing materials (e.g. chip seal, soil organic binder) would extend hauling periods and may allow all-weather hauling.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #5

Resource Sensitivity:	ARS R-1 South Fork and Mainstem of the Nooksack River and the historic meander belts (<0.001).
Input Variables:	Large woody debris
Hazard:	Moderate or High
Vulnerability:	High (Fish habitat)
Rule Call:	Prevent or avoid

Situation Statement:

Conversion of the pre-settlement forest to agricultural land use has removed conifers and large deciduous trees from the floodplain of the South Fork and Mainstem of the Nooksack. This has greatly reduced recruitment of functional LWD to the channel and floodplain, thereby reducing channel complexity and habitat diversity. Floodplain modifications, including diking the mainstem, straightening the meanders, and draining slough channels, have greatly reduced the total area of riparian habitat on the floodplain. These floodplain modifications represent the largest and most persistent negative impact on fish habitat in the Acme WAU.

Triggering Mechanism(s):

Conversion of forest lands to non-forest production uses, primarily agriculture, has entailed a large net loss of riparian habitat and removed conifers and large hardwood trees. The residual riparian trees in non-forest lands typically consist of a thin screen of young hardwood trees along the streamside. Remaining areas of forest land consist of a dense forest of young hardwoods. LWD from young hardwoods decays swiftly and is subject to rapid downstream transport, and thus has little habitat value.

Prescriptions:

No harvest can occur on or within 100 feet horizontally of the historical meander belt (AKA channel migration zone - see definition from Forests and Fish Report dated February 22, 1999 in Appendix. 11-7).

Technical Rationale:

Application of this prescription for current conditions will have little effect on LWD recruitment and in-channel retention while the river is maintained in a constricted channel that provides few sites for LWD accumulation. Non-forest land uses currently preclude development of riparian forests adjacent to the river channel.

This prescription will tend to remedy these problems and will provide improved fish habitat. This prescription , accompanied by relocation of existing dikes and rip-rap, will provide more extensive and greater improvement in fish habitat while possibly reducing flooding in downstream reaches.

Protection of a meander belt would allow the river to meander freely. Under such conditions, high streamflows from the South Fork and Mainstem of the Nooksack could deposit LWD in existing slough channels and would occasionally excavate new slough channels. The 100-foot no-cut buffer adjacent to the historical meander belt is necessary to maintain LWD recruitment to such channels at a sufficiently high level.

Voluntary Remedial Opportunity:

Relocation of dikes and rip-rap to the limits of the identified historical meander belt (approximately equivalent to the 50-year floodplain) would allow the South Fork and Mainstem of the Nooksack to meander naturally, thereby creating slough channels and interacting (exchanging sediment, wood and water) with its floodplain. The Department of Natural Resources shall relay the importance of this opportunity to Whatcom County officials so that funding sources, zoning laws, and other pertinent regulations can be modified/created to facilitate relocation.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #6

Resource Sensitivity:	ARS R-2 Floodplain tributaries (< =0.04) not including alluvial fans.
Input Variables:	Large woody debris
Hazard:	Moderate or High
Vulnerability:	High (Fish habitat)
Rule Call:	Prevent or avoid

Situation Statement:

Conifers and large deciduous trees were removed from the riparian zone during conversion to agricultural usage, thus eliminating recruitment of LWD. Channel manipulations have largely removed in-channel LWD, thereby degrading fish habitat by reducing channel stability and complexity.

Triggering Mechanism(s):

Conversion of the pre-settlement forest to agricultural land uses has eliminated large trees and conifers from the riparian zone. Existing regrowth of small hardwood trees, limited to narrow corridors along the channels, produce woody debris which is relatively mobile and prone to rapid decay. Cutting these trees for timber or other reasons would further delay input of functional LWD.

Prescriptions:

No harvest can occur within 100 feet horizontally of the ordinary high water mark of anypotential fish habitat as defined under current Forest Practice Rules at the time of application.

Technical Rationale:

Studies cited in the riparian assessment suggest that a buffer width of 100 feet is necessary to ensure that the stream channels receives 90% of potential LWD recruitment and 90% of potential shade.

Voluntary Remedial Opportunity:

Establishment of riparian forests in agricultural areas is desirable.

Artificial placement of large woody debris in pseudo-natural configurations could be effective for improving fish habitat, but only in channels not experiencing high inputs of coarse sediment.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #7

Resource Sensitivity:	ARS R-3 Alluvial fans (>0.04 and < =0.09).
Input Variables:	Large woody debris
Hazard:	Moderate or High
Vulnerability:	High (Fish habitat)
Rule Call:	Prevent or avoid

Situation Statement:

Conifers and large deciduous trees have been eliminated from the riparian zone and other parts of alluvial fans, largely by conversion to agricultural usage, thus reducing LWD recruitment potential. Channel manipulations have largely removed in-channel LWD, thereby degrading fish habitat by reducing channel stability and complexity. Removal of large trees has also reduced the role of "barrier trees", which may reduce runout lengths of debris flows and dam break floods, potentially reducing damage to property and habitat.

Triggering Mechanism(s):

Conversion of the pre-settlement forest to agricultural land uses has eliminated large trees and conifers from the riparian zone. Selective timber harvest and residential development (i.e. Jones Creek) have reduced densities as well. Small residual hardwood trees produce woody debris which is relatively mobile and prone to rapid decay.

Prescriptions:

No harvest can occur within 100 feet horizontally of the ordinary high water mark of any potential fish habitat on the alluvial fans as defined under current Forest Practice Rules at the time of application. No harvest can be made of any trees growing in the barrier tree zone of the alluvial fan. The barrier tree zone contains all portions of the alluvial fan lying within 300 feet horizontal distance (660 feet in the case of Jones Creek) of the point where water from the upstream channel segment flows onto the alluvial fan (Figure 11-1). Other trees growing on the alluvial fans may be harvested, provided that all of the following conditions are met:

1. A maximum of thirty percent (30%) of the merchantable (> = 12 inch DBH) trees may be cut in any ten (10) year period.
2. The diameter distribution of merchantable trees must be maintained or shifted toward a larger average diameter. The percent of conifer stems shall be retained or increased, as well.
3. Residual merchantable trees shall be relatively evenly spaced.

4. Minimum stocking levels for live residual merchantable trees is 75 trees per acre with a minimum diameter of 12 inches.

The lower and lateral boundaries of the alluvial fan can be delineated by finding the point of channel gradient change and projecting that elevational contour in both directions across the landscape to the points at which the projected contour no longer arcs back towards the upstream channel segment.

Technical Rationale:

Alluvial fans are important spawning and rearing areas and warrant protection. Because of frequent debris recruitment by avulsion (i.e. rapid shifting of channel location during high flow events) and lateral channel migration, the 100-foot no-cut requirement is necessary to maintain the supply of large woody debris.

Trees growing on the upper portions of alluvial fans can serve as barriers to debris flows or dam-break floods. The 300 feet no-cut requirement at the apex of an alluvial fan ensures that these barrier trees will be retained. However, the degree of protection provided by this zone against debris flows and dam-break floods is not absolute, even with mature trees. The Jones Creek alluvial fan is particularly large and dam-break floods delivering to that fan could have severe impacts to public and private works; therefore an enlarged barrier tree zone is of greater value than elsewhere.

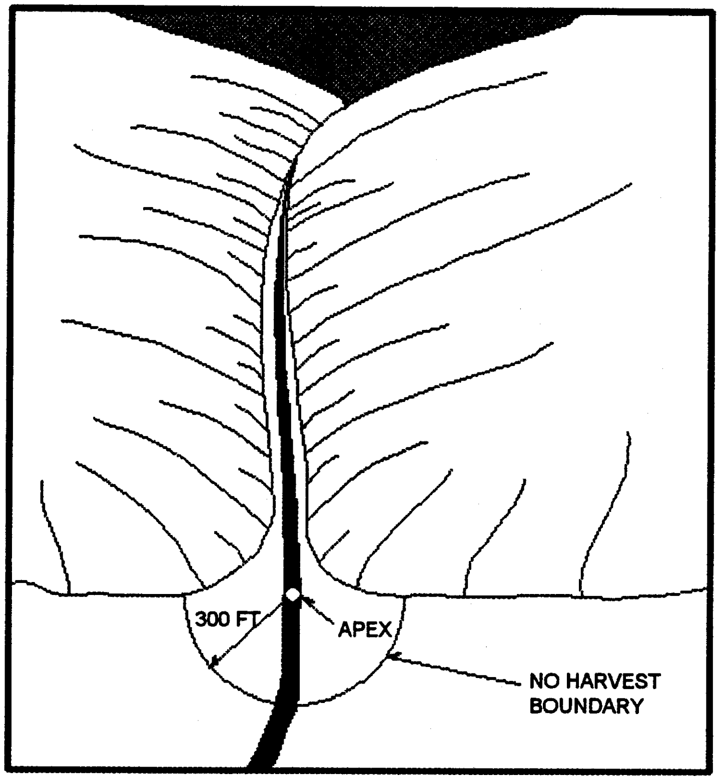
Even under natural conditions, channels on the alluvial fans move relatively frequently. The 30% harvest limitation, along with the distribution and spacing requirements, ensure that the average diameter of alluvial fan stands will increase towards trees large enough to contribute functional LWD and that these large trees will be distributed wherever new channels might be formed by avulsion.

Voluntary Remedial Opportunity:

Establishment of riparian forests in agricultural areas is desirable.

Artificial placement of large woody debris in pseudo-natural configurations could be effective for improving fish habitat, but only in channels not experiencing high inputs of coarse sediment.

Figure 11-1. Barrier tree zone placement.



CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #8

Resource Sensitivity:	ARS R-4 Mountain channels (>0.09) and Upland channels below small lakes (0.02-0.06)
Input Variables:	Large woody debris
Hazard:	Moderate or High
Vulnerability:	High (Fish habitat).
Rule Call:	Prevent or avoid

Situation Statement:

Conifers and large deciduous trees have been eliminated from the riparian zone along mountain streams by timber harvest, thereby limiting new recruitment of large woody debris and resulting in degraded fish habitat through a reduction in channel stability and complexity.

Triggering Mechanism(s):

Logging of the pre-settlement forest eliminated large trees and conifers from the riparian zone. Debris flows triggered upslope have also delayed the regeneration of conifers along streams. Small residual and regenerating hardwood trees produce woody debris which is relatively mobile and prone to rapid decay.

Prescriptions:

For the purposes of these prescriptions, the anadromous fish barriers are approximately mapped and are the points on the streams where the lowest falls with a vertical drop of 10 feet or more exist or the stream gradient exceeds 20 percent.

Below Fish Barrier

No harvest within 100 feet horizontally of potential fish habitat as defined under current Forest Practice Rules at the time of application.

Minimal tree removal may be permitted to provide corridors for full-suspension skyline yarding provided that:

A. Skyline yarding would avoid otherwise necessary road construction, particularly when the only road access option would require road construction across these channels.

B. Corridor placement results in minimal cutting of trees.

C. Location of corridors shall be free of significant signs of instability.

D. Falling and yarding operations shall result in minimal soil disturbance.

E. Total corridor area shall not exceed 15% of the riparian area in the harvest unit.

Above Fish Barrier

No harvest within 50 feet horizontally of potential fish habitat as defined under current Forest Practice Rules at the time of application. Minimal tree removal may be permitted to provide corridors for full-suspension skyline yarding according to the conditions noted above.

Technical Rationale

Protection of non-fish habitat segments of these channels is likely provided for under the mass wasting prescriptions or under the "Riparian Prescription in Lieu of Causal Mechanism Report".

Voluntary Remedial Opportunity:

Thin young, over-stocked hardwood stands to release existing conifer seedlings and/or interplant additional shade-tolerant conifer seedlings. Thinning young dense hardwood stands to release established conifers would accelerate production of functionally-sized woody debris and likely represents the most effective means of achieving prescription targets. In other instances, underplanting shade-tolerant conifer species may help accelerate the growth of large, decay-resistant woody debris for the future.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #9

Resource Sensitivity:	ARS R-5 Channel Segments 1,2,4,5,6,7, and 8.
Input Variables:	Shade
Hazard:	High
Vulnerability:	High (Fish habitat)
Rule Call:	Prevent or avoid

Situation Statement:

Open riparian canopy along many channel segments does not cast shade sufficient to meet target levels, potentially increasing stream temperatures in these segments and downstream. Increased summer temperatures impair the function of these streams as salmonid rearing and holding habitat.

Triggering Mechanism(s):

Reduced riparian canopy is the result of land clearing for agricultural development and of timber harvesting. Reduced riparian canopy closure can adversely affect stream temperatures for salmonids by increasing the exposure to solar radiation.

Additionally, factors that increase the rate of exchange of stream waters and groundwater may adversely affect temperatures in large streams. Such factors for the South Fork include cutting the floodplain forests and the loss of most of the floodplain wetlands, resulting in a lowered low flow water table. Another factor is the loss of channel complexity due to diking of 60% the channel length, and the attrition/removal of 100% of the full spanning LWD jams. This has resulted in an 87% reduction in slough channels, a 40% reduction in the area of gravel bars, and a 50% reduction in sharp-angled (>60 degree) meander bends in this reach of the South Fork. Temperature impacts are likely to have occurred from reduced groundwater flow under gravel bars or across meander bends. Additionally sharp-angled channel meanders often develop very deep pools that may be thermally stratified and provide refugia habitat.

Prescriptions:

No harvest of any riparian canopy cover can occur within 100 feet horizontally of fish habitat as defined under current Forest Practice Rules at the time of application until adequate shade levels are recovered. Nor can harvest of any riparian canopy cover occur within 100 feet horizontally of the ordinary high water mark of the first 1000 feet upstream of fish habitat until adequate shade levels are recovered. Adequate shade levels will be determined according to the temperature prediction method described by WAC 222-30-040.

Technical Rationale:

Existing shade levels are not adequate to prevent temperature increases. Once adequate shade levels return, then timber harvesting can resume provided that riparian canopy cover is maintained at adequate shade levels. Existing shade levels are correlated with land use. Ninety-six percent of channels in agricultural areas were below target shade, and thirty-three percent of channels in forested areas were below target shade.

South Fork low flow temperatures can approach lethal thresholds for salmonids. This is of concern for adult migration and holding for spring/summer chinook, pink salmon, summer steelhead, and Dolly Varden/bull trout. Additionally, summer juvenile rearing habitat is impaired for all juvenile salmonids that would be expected to rear in the lower South Fork including stream type spring/summer chinook, coho, steelhead and cutthroat trout. Cooler areas including the lower portions of accessible tributaries, seeps, and other groundwater influenced areas including deep pools probably provide critical juvenile refugia habitat.

Voluntary Remedial Opportunity:

Establishment of riparian forests in agricultural areas is highly desirable. Protection of floodplain wetlands is also very important.

Relocation of dikes and rip-rap to the limits of the identified historic meander belt (approximately equivalent to the 50-year floodplain) would allow the South Fork Nooksack River to meander naturally. This would increase the number of sharp-angled meander bends, thereby increasing the number of very deep pools. Restoring the meander belt would also increase the river's ability to form point bars (gravel bars) resulting in increased groundwater flow under gravel bars and across meander bends. Remediating the adverse summer temperatures in the South Fork is unlikely to be successful if stream shade is viewed as the only cause. The Department of Natural resources shall relay the importance of this opportunity to Whatcom County officials so that funding sources, zoning laws, flood hazard reduction, and other pertinent regulations can be modified/created to facilitate dike and rip-rap relocation.

RIPARIAN PRESCRIPTION IN LIEU OF CAUSAL MECHANISM REPORT

Assessment of large woody debris recruitment for Type 4 streams was not required by the version of Standard Methodology for Conducting Watershed Analysis under which this analysis was initiated. Member of the prescription team expressed concerns that large woody debris recruitment would not exist along any Type 4 streams not subject to mass wasting prescriptions. To ensure a minimum level of large woody debris recruitment, all timber harvest operations are required to leave at least 25 conifer or deciduous trees, 6 inches in diameter or larger, on each side of every 1000 feet of stream length within 25 feet of Type 4 streams.

CAUSAL MECHANISM AND PRESCRIPTION REPORT
Acme WAU
Report #10

Resource Sensitivity: ARS WQ-1
Input Variables: Shade
Hazard: High
Vulnerability: High or Moderate
Rule Call: Prevent or avoid

Situation Statement:

Open forest canopy adjacent to small wetlands (<10 acres) may not cast sufficient shade sufficient to prevent elevation of wetland water temperatures, potentially degrading water quality.

Triggering Mechanism(s):

Reduced wetland management zone canopy is the result of land clearing for agricultural development and of timber harvesting.

Prescriptions:

Standard wetland management zone rules (WAC 222-30-020-7) apply except for the following:

1. The average WMZ width for Type B wetlands less than or equal to five acres shall be 50 feet.

2. Required leave trees shall be relatively evenly spaced.

3. Openings larger than dictated by spacing requirements (approximately 24 feet) are prohibited.

Technical Rationale:

Standard rules could allow harvesting of all WMZ canopy on the southern edges of small Type A and Type B wetlands. The prescribed modifications ensure that adequate canopy will be distributed around the edges of such wetlands. The assessment classified four forested wetlands as depressional flow-through because of stream association. Because such wetlands are sufficiently protected by riparian shade and LWD prescriptions, no additional prescriptions were generated.

Form G-1. Wetland Assessment Worksheet

Wetland Identifier	Wetland Hydro-geomorphic Class and subclass	Legal Location	NWI Code	DNR Wetland Class/Type	Wetland Area (acres)	Open Water Area (acres)	Season Observed	Input Variable	Vulnerbility Call
S01-1	DFT	17-37N-5E	PSSC	B	7	0	5/26/95	Sediment	Low
S03-1	DC	2-37N-4E		B	1	0	5/26/95	Sediment	Mod
S03-2	DC	1-37N-4E		B	1	0	5/26/95	Sediment	Mod
S08-1	DC	5-38N-5E		B	3	0	5/26/95	Sediment	Mod
S08-2	DC	5-38N-5E		B	2	0	5/26/95	Sediment	Mod
S08-3	DFT	4-38N-5E	PSSC	A	7	3	5/26/95	Sediment	Low
S08-4	DFT	4-38N-5E		B	1	0	5/26/95	Sediment	Low
S08-5	DFT	4-38N-5E	PSSC	A	2	1	5/26/95	Sediment	Low
S08-6	DFT	4-38N-5E	PSSF	A	7	1	5/26/95	Sediment	Low
S09-1	DFT	7-38N-5E	PFOC	B	8	0	5/26/95	Sediment	Low
S10-1	DFT	8-38N-5E		B	1	0	5/26/95	Sediment	Low
S10-2	DFT	8-38N-5E	PSSC	B	7	0	5/26/95	Sediment	Low
S10-3	DFT	4-38N-5E	PSSC	A	11	2	5/26/95	Sediment	Low
S10-4	DFT	10-38N-5E		F	3	0	5/26/95	Sediment	Low
S10-5	DFT	10-38N-5E		B	2	0	5/26/95	Sediment	Low
S10-6	DFT	10-38N-5E		B	1	0	5/26/95	Sediment	Low
S11-1	DFT	32-38N-5E		B	5	0	5/26/95	Sediment	Low
S11-2	DFT	8-38N-5E	PSSC	B	11	0	5/26/95	Sediment	Low
S11-3	DFT	17-38N-5E	PSSC	B	12	0	5/26/95	Sediment	Low
S11-4	DFT	19-38N-5E		F	1	0	5/26/95	Sediment	Low
S11-5	DFT	20-38N-5E	PEMA	B	11	0	5/26/95	Sediment	Low
S12-1	DFT	22-38N-5E		F	7	0	5/26/95	Sediment	Low
S12-2	DFT	21-38N-5E		F	2	0	5/26/95	Sediment	Low
S12-3	DFT	15-38N-5E		B	5	0	5/26/95	Sediment	Low
S12-4	DFT	15-38N-5E		B	7	0	5/26/95	Sediment	Low
S12-5	DFT	27-38N-5E	PSSF	B	3	0	5/26/95	Sediment	Low
S12-6	DFT	27-38N-5E	PSSC	B	3	0	5/26/95	Sediment	Low
S01-1	DFT	17-37N-5E	PSSC	B	7	0	5/26/95	Temperature	Mod
S03-1	DC	2-37N-4E		B	1	0	5/26/95	Temperature	High
S03-2	DC	1-37N-4E		B	1	0	5/26/95	Temperature	High
S08-1	DC	5-38N-5E		B	3	0	5/26/95	Temperature	High
S08-2	DC	5-38N-5E		B	2	0	5/26/95	Temperature	High
S08-3	DFT	4-38N-5E	PSSC	A	7	3	5/26/95	Temperature	Mod
S08-4	DFT	4-38N-5E		B	1	0	5/26/95	Temperature	High
S08-5	DFT	4-38N-5E	PSSC	A	2	1	5/26/95	Temperature	High
S08-6	DFT	4-38N-5E	PSSF	A	7	1	5/26/95	Temperature	High
S09-1	DFT	7-38N-5E	PFOC	B	8	0	5/26/95	Temperature	Mod
S10-1	DFT	8-38N-5E		B	1	0	5/26/95	Temperature	High
S10-2	DFT	8-38N-5E	PSSC	B	7	0	5/26/95	Temperature	Mod
S10-3	DFT	4-38N-5E	PSSC	A	11	2	5/26/95	Temperature	Low
S10-4	DFT	10-38N-5E		F	3	0	5/26/95	Temperature	High
S10-5	DFT	10-38N-5E		B	2	0	5/26/95	Temperature	High
S10-6	DFT	10-38N-5E		B	1	0	5/26/95	Temperature	High
S11-1	DFT	32-38N-5E		B	5	0	5/26/95	Temperature	Mod

Form G-1. Wetland Assessment Worksheet

Wetland Identifier	Wetland Hydro-geomorphic Class and subclass	Legal Location	NWI Code	DNR Wetland Class/Type	Wetland Area (acres)	Open Water Area (acres)	Season Observed	Input Variable	Vulnerbility Call
S11-2	DFT	8-38N-5E	PSSC	B	11	0	5/26/95	Temperature	Low
S11-3	DFT	17-38N-5E	PSSC	B	12	0	5/26/95	Temperature	Low
S11-4	DFT	19-38N-5E		F	1	0	5/26/95	Temperature	High
S11-5	DFT	20-38N-5E	PEMA	B	11	0	5/26/95	Temperature	Low
S12-1	DFT	22-38N-5E		F	7	0	5/26/95	Temperature	Mod
S12-2	DFT	21-38N-5E		F	2	0	5/26/95	Temperature	High
S12-3	DFT	15-38N-5E		B	5	0	5/26/95	Temperature	Mod
S12-4	DFT	15-38N-5E		B	7	0	5/26/95	Temperature	Mod
S12-5	DFT	27-38N-5E	PSSF	B	3	0	5/26/95	Temperature	High
S12-6	DFT	27-38N-5E	PSSC	B	3	0	5/26/95	Temperature	High

APPENDIX 11-1

Project Report (Appendix 3-3 in Mass Wasting Module)
Analysis of Slope Gradients of Shallow Landslides in Bedrock Hollows
in the Acme WAU

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Geomorphologist
Lee Benda and Associates, Inc.

Introduction

During the original mass wasting assessment conducted in the Acme WAU in support of a watershed analysis it was estimated that between 65% to 88% of shallow landslides in hollows occurred on slope gradients greater than 36° (73%) (pg. 3-4, Mass Wasting Module). This was based on analysis of aerial photography, limited field surveys, other landslide studies, and the experience of the analyst in the surrounding area. Hence, it was concluded that the highest potential hazards were associated with convergent topography in excess of 36°. A lower landslide risk should occur on lower hillslope gradients.

During the prescription phase of the Acme watershed analysis there was concern among some team members (DNR and the Lummi Tribe) that an abrupt gradient cutoff of 36°, which was proposed to characterize high risk landslide terrain, would not account for landsliding at gradients below 36°, specifically between 31° (62%) and 35° (70%). As a consequence, during the prescription process hollows with gradients in excess of 36° were classified as "high-hazard bedrock hollows" and hollows with gradients between 31° and 35° as "moderate-hazard bedrock hollows". Furthermore, the prescription team decided to treat both slope categories similarly with respect to road and harvest management prescriptions. For example, a no harvest recommendation was made for the unstable portion of bedrock hollows (e.g., all hollows greater than or equal to 31°).

Since the initial mass wasting assessment continuing informal field observations of unstable areas in the Acme area made by personnel from the Trillium Corporation, Crown Pacific Corporation, and by this author indicated that the vast majority of shallow slides in hollows occurred on slopes greater than or equal to 36° (also see Appendix 3-2 in Mass Wasting Module, Acme Watershed Analysis). Hence, the Crown Pacific Corporation, which is presently in the process of reviewing the Acme watershed analysis and its prescriptions, proposed a field inventory of recent landslide scars to more accurately determine the range of slope gradients in bedrock hollows that have been associated with shallow failures. Below is a summary of those findings.

The objective of the field survey was to more accurately determine the relative proportion of landslides in hollows in recent clearcuts that were associated with one of two slope gradient classes: 31 – 35 degrees and greater than or equal to 36 degrees. It was not possible to verify in the field all of the landslide gradients that were measured using topographic maps during the original Acme watershed analysis because of time limitations due to winter weather and access difficulties. To determine the field-based frequency distribution of landslide gradients in the Acme area, 14 landslides that occurred in clearcuts were selected randomly. To this population was added five landslides studied by Buchanan (1988). This sample population did not include any of the slides originally estimated to be between 31 and 35 degrees based solely on topographic maps. Nevertheless, the field-based distribution of gradients should be considered a more accurate representation of bedrock hollows prone to landsliding in the sandstone portion of the Acme WAU than estimates based solely on topographic maps.

Landslide site locations are shown in Figures 1 and 2. The five landslides studied by Buchanan (1988) include his sites W-1, W-2, DD-1, DD-2, and DD-3. Slope gradients of the headscarp area (distances of approximately several tens of meters) were measured using a clinometer and widths of landslide scars were visually estimated (Table 1). A frequency histogram shows the range and distribution of the slope gradients at the landslide scars (Figure 3).

Seventeen slides in hollows (which delivered sediment to channels), or 89%, had gradients greater than or equal to 36^{o} (73%). Of the two remaining slides, one had a gradient of 35^{o} (70%) and the another 32^{o} (62%); the latter slide may have been associated with road drainage. The mean gradient of all nineteen slides is 37.5^{o} (77%). For comparison, approximately 22% of landslides located in hollows in clearcuts (landslides which delivered sediment to channels but which did not include those in the phyllite terrain) measured from topographic maps during the original watershed analysis had map-measured gradients of 31 – 35 degrees.

It was observed in the field that several of the landslide scars occurred in shallow bedrock hollows (e.g., non pronounced bedrock concavities); this was also determined by Buchanan (1988) who referred to them as "wedges". In the field landslides in wedges were usually connected to an incised first-order stream valley which allowed propagation of the slide as a debris flow. Hence, to aid in the field detection of all steep convergent areas prone to failure, one or more soil wedges should be anticipated at the heads of steep, incised first-order channels, in addition to more well developed bedrock hollows. In addition, widths of landslide scars ranged from 4 m (13 ft) to 12 m (40 ft) and averaged 7 m (23 ft). This information could be used to help determine the size of leave areas in hollows for the purpose of maintaining buffer strips.

From a forest management perspective regarding timber harvesting, the results of the landslide inventories indicate that prescriptions which focus on bedrock hollows with gradients >= 36^{o} will cover about 90% of those landslide source areas (e.g., in convergent areas underlain by sandstone bedrock) Ten percent of the landslide source areas in hollows will not be addressed by a harvest prescription. If a prescription to mitigate road-related landsliding were developed and applied to 31 to 35^{o} bedrock hollows, the proportion of all potential hollow landslide sites addressed by prescriptions should increase above 90%.

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Buchanan, P. (1988) Debris avalanche and debris torrent initiation, Whatcom County, Washington, U.S.A. Unpublished MS thesis, University of British Columbia, 236 pp.

Table 1. Hillslope gradients and widths of landslide scars obtained at landslide headscarps.

Landslide #	Source	Axis Gradient (degrees)	Landslide Inventory #	Inventory Gradient (degrees)	Scar Width (m)
1	This survey	39	98	>=36	6
2	This survey	37	Na[2]		5
8	This survey	40	38	>=36	12
4	This survey	38	Na[2]		6
5	This survey	42	105	>=36	6
6	This survey	39	106	>=36	7
7	This survey	38	107	>=36	9
8	This survey	36	94	>=36	6
9	This survey	32[1]	96	>=36	6
10	This survey	36	95	>=36	8
11	This survey	36	34	>=36	4
12	This survey	39	104	>=36	6
13	This survey	36	Na[3]		7
14	This survey	38	Na[3]		10
15	Buchanan(1988)	39	Na[3]		
16	Buchanan(1988)	36	Na[3]		
17	Buchanan(1988)	35	Na[3]		
18	Buchanan(1988)	39	Na[3]		
19	Buchanan(1988)	37	Na[3]		

[1] could be road related
Na[2] Not included in original inventory
Na[3] Outside of original inventory area

Figure 1. Upper watershed areas in the Acme WAU showing the locations of recent landslides where measurements of headscarp gradients were made.

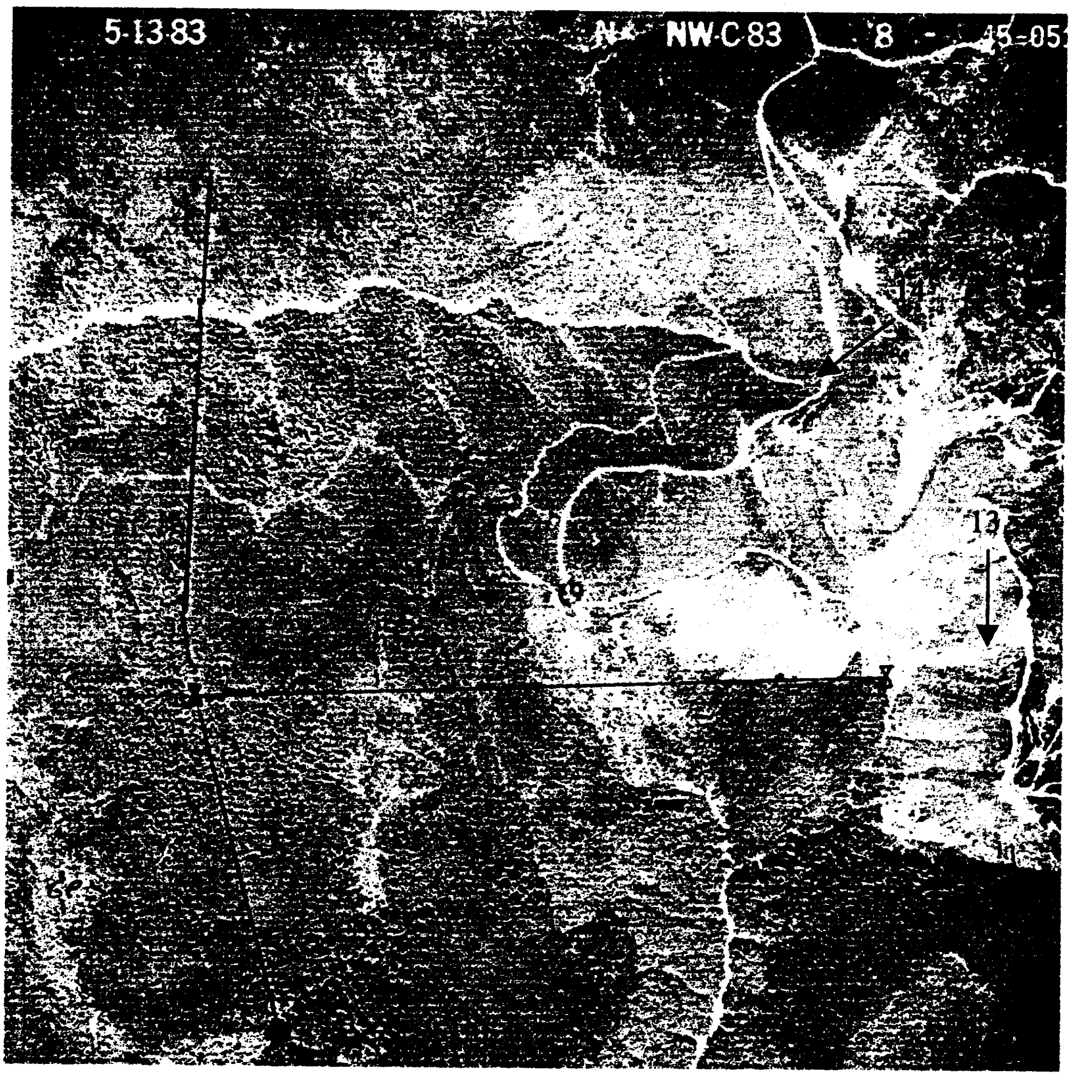

Figure 2. Upper watershed areas draining into Lake Whatcom where gradients of landslides were obtained.

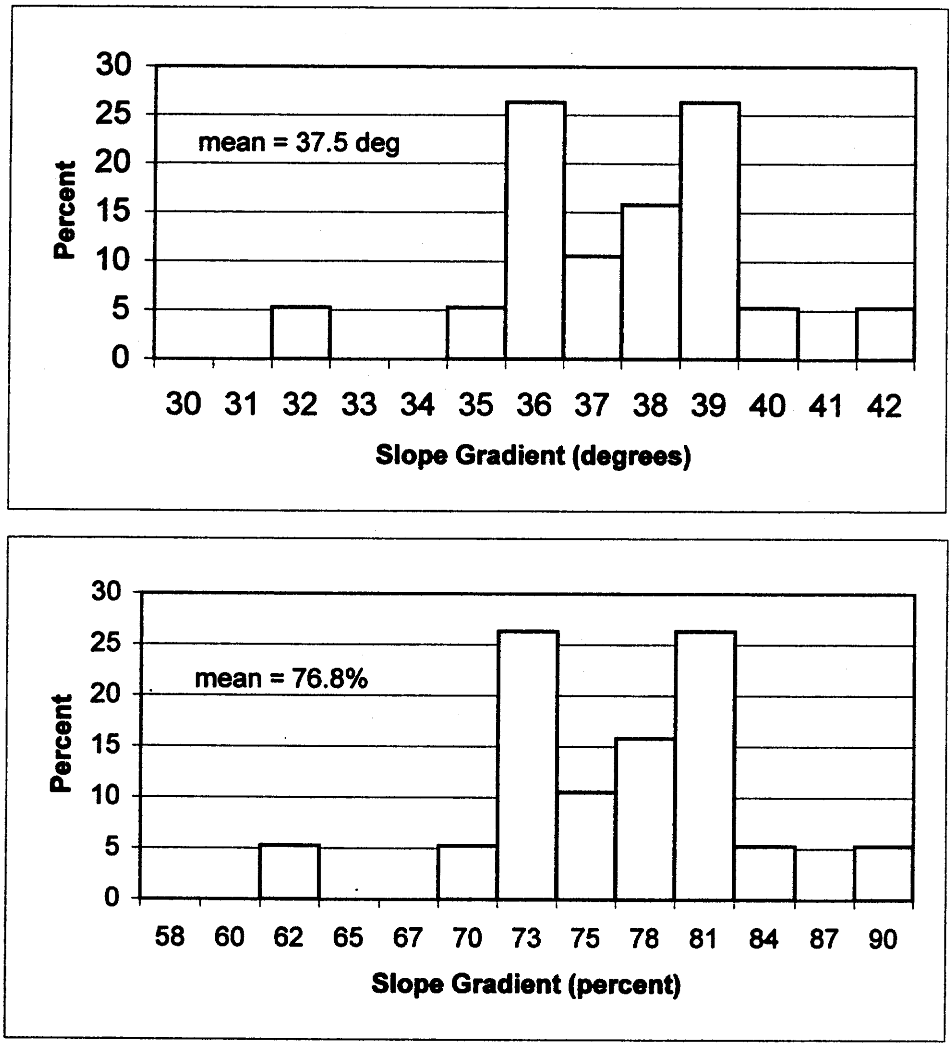

Figure 3. Histogram of nineteen field-measured gradients of recent landslide scars in bedrock hollows. Five of the sites were measured by Buchanan(1988).

APPENDIX 11-2

Method to Predict Landslide Runout on Non-Convergent Hillslopes

Lee Benda Ph.D.

Background

The degree to which landsliding is considered an environmental impact depends in large part on the delivery of landslide debris to stream channels. Many factors govern the travel distance, or runout, of landslide debris including landslide volume, topography over which landslides travel (slope gradient, slope form, roughness etc.), debris thickness, water content, and the grain size distribution of the debris. Following failure, landslides typically liquefy as the saturated soil mass and its reinforcing network of roots break up. When landslide debris enter and flow within small, steep stream channels they are referred to as debris flows. Debris flows typically contain 70 to 80% soil and only 20 to 30% water. Erosion of additional sediment and organic debris in small and steep channels can increase the volume of the original landslide by 1000% or more (Benda and Cundy, 1990). Debris flows in channels can runout thousands of meters on relatively low-gradient slopes (5 – 20%), in part, because the confined nature of channels results in increased flow thickness which enhances runout and prevents deposition. Methods for predicting the approximate location of debris flow runout in confined mountain channels has been developed (Benda and Cundy, 1990; Fannin and Rollerson, 1993). Such methods could also be combined with models that consider runout of debris on fans due to momentum (Takahashi and Yoshida, 1979).

Runout of landslide debris can also occur over non-convergent slopes. In general, less is known about this form of landslide runout compared to channelized debris flows. Some sediment delivery rules have been proposed for specific geographic areas where field observations on runout characteristics were available (Collins et al., 1994; Forest Practices Code of British Columbia). However, the lack of testing limits the extrapolation of these methods to other areas.

Sediment Delivery Model for Non-Convergent Hillslopes

A sediment delivery model for non-convergent hillslopes is described below (e.g., non channelized landslides). The model is based on the theoretical principle and empirical finding that moving landslide debris contains a relatively rigid (non shearing) raft, or plug, of debris on the surface, a rheology referred to as coulomb-viscous (Johnson, 1984). Semi-liquefied landslide debris that moves downslope, and which does not continue to trigger additional landslides beneath the moving debris (see later), will spread, thin, and deposit. Landslide debris should stop moving when the debris has thinned to a point where it equals the thickness of the non-shearing rigid layer. Thickness of the landslide debris at deposition, referred to as its critical thickness, is governed by the shear stress in the debris and the resistance of the debris to shear, the latter property referred to as a yield strength (Johnson, 1984). With a varying shear stress within the landslide debris caused by gravity on an inclined surface and a constant yield strength, the critical thickness will vary with hillslope gradient and increase with decreasing gradient.

A series of environmental factors govern the runout of landslide debris using the coulomb-viscous model including the initial volume of the landslide, the moisture content of the debris expressed as the unit weight of material (kg/m^3 multiplied by acceleration of gravity), the slope of the hillslope over which the debris is moving, the yield strength of the debris, and roughness of the slope (standing trees, stumps etc.,). The latter factor is ignored in the present analysis, although increased roughness should lead to shorter travel distances. The yield strength of the debris is dependent on many site specific factors, including grain size distribution, percent of silt and clay, and moisture content (Innes, 1985; Benda, 1988).

Johnson (1970, 1984) derived equations of shear stress and motion for landslide debris (referred to as debris flows) for both confined and wide channels. In wide channels (which would be applicable to a non-convergent hillslope where spreading of the debris would create a geometry of flow with debris thickness is some small fraction of its width), the relationship between yield strength of the debris (K), critical thickness (T_c), hillslope gradient (y), and the unit weight of the material (Q) is given by:

$$T_c = K/(Q \sin(y)) \qquad (1)$$

Yield strength of landslide debris can be estimated using (1) by measuring the deposit thickness of landslides (or debris flows) in the field, along with estimates of the unit weight of debris and the slope on which the debris deposited (Johnson, 1984). Thicknesses of landslide deposits in the region are commonly on the order of one to two meters on slopes of three to six degrees (Benda, 1988; unpublished data). Unit weight of liquefied landslide debris (debris flows) has been estimated to be approximately 18000 nt m^{-3} (Benda, 1988). These values should apply in general to many areas in western Washington. Exceptions may include clay-rich landslides originating from glacial deposits and estimates of material properties may change in those cases. Using these values, including a deposit thickness of 1.5 m at a slope of 5 degrees in (1), gives a yield strength of approximately 1500 nt m^{-2}.

According to (1), the critical thickness of the debris (T_c) is dependent on the hillslope gradient. Using the estimate of yield strength of landslide debris of 1500 nt m^{-2} allows the calculation of the dependence of critical thickness on slope angle (Figure 2). The critical depth, or depth of the deposition layer (T_c), varies with hillslope gradient and ranges from less than 0.25m on hillslopes of about 30° (58%) to about 1m on hillslopes of about 5° (9%) (Figure 1). Hence, thickness of deposition will vary along the flow path of a landslide in non-channelized environments (relatively planar hillslopes).

Landslide debris that moves down non-convergent hillslopes spreads laterally unless constrained by objects on the hillslope including micro topography, logs, stumps, standing trees etc. An idealized flow path of landslide debris on non-convergent, or planar topography, is shown in Figure 2. Runout of landslide debris along the flow path is governed by the volume of the landslide, the thickness of the debris during deposition, referred to as the critical thickness, the width of the landslide at the beginning of its runout, and the angle of spread (B in Figure 2). Hence, the relationship between landslide volume and runout length is:

$$V = [(W_oL) + (L^2 \sin B)]*T_c \qquad (2)$$

where V is the initial landslide volume (additional failure or scour of hillslopes is not covered by this model, see next section below), L is the landslide length or runout, W_o is the initial width of flow or landslide scar width, T_c is the critical deposit thickness (from Figure 1), and B is the spread angle. With a non-varying landslide volume, the runout distance (L), using the idealized flow geometry in Figure 2, can be represented as a quadratic function of landslide volume (V):

$$L(V) = [((T_cW_o)^2 - 4(T_c \sin B(V)))^{1/2} - T_cW_o]/2(T_c \sin B) \qquad (3)$$

Equations (2) and (3) assumes that the velocity profile of the moving debris is parabolic with the highest velocity at the surface (Johnson, 1984). Hence, the top layers of the debris would shear and move on top of the basal layer(s). This process of thinning, directly downslope and laterally controlled by the spread angle, would eventually create a layer of debris which would stop moving. The deposit layer would have a thickness governed by the yield strength of the debris in relation to the shear stress, or a critical thickness (Figure 1).

Parameters for use in (3) can be obtained from field studies or landslide inventories. For example, a typical width of a landslide in the Chuckanut formation located in northwestern Washington is about 4 to 8 m and a spread angle of 4.3 degrees has been measured in the same area (Buchanan, 1988). Likewise, a characteristic landslide volume can be obtained from field measurements. Estimates of landslide runout as a function of landslide volume are made using a range of critical thicknesses, 0.25m to 0.75m representing slope angles of 30^0 to 6^0 (Figure 1). Using a W_0 of 8m and a spread angle of 4.3° (from Buchanan, 1988), the predicted landslide runout is plotted in Figure 3. For example, given a landslide volume of about 350 m^3 (455 yd^3), the predicted runout distance ranges between 40 and 80 m (130 to 260 ft) (Figure 3). The range of critical thickness indicates that the runout will be closer to 130 ft on low-gradient areas, such as flat valley floors or fans, and runout will approach the higher value on steeper slopes.

Field estimates of slope length are necessary to compare with predictions of landslide runout and delivery to estimate delivery hazards (see below). Slope length estimates are made on a site specific basis and will reflect various topographies. Estimates of slope length can be made above slope breaks, on slopes directly adjacent to stream channels, and along hillslopes *and* valley floors (Figure 4).

Application of the Coulomb-Viscous Landslide Delivery Model

The runout model (Equation 3 and Figure 3), referred to hereafter as the Coulomb-viscous model, requires that the volume of a landslide does not increase during the duration of the runout. Landslides that are triggered within, or runout into, convergent areas, such as debris flows in first- and second-order channels, commonly increase their volumes downstream by scour of channel beds (Benda and Cundy, 1990). Furthermore, confined headwater channels prevent spreading and landslide debris maintains depths much in excess of critical thicknesses, allowing long runouts.

Steep, non-convergent slopes (e.g., unchannelized) that are near saturation may be meta stable and have a factor of safety near 1. [Factor of safety is the ratio of stabilizing to destabilizing forces on a hillslope. When factor of safety is less than one, failure is predicted.] Landslide debris that travels on top of a meta-stable hillslope could conceivably contribute to failure by loading the slope with additional weight and scouring of vegetation. Hence, equation (3) only applies to those hillslopes where additional failures beneath moving landslide debris is unlikely. The hillslope gradient, in combination with underlying lithology, slope length, soil thickness, soil mechanical strength, rooting strength, and porosity that defines such potentially unstable areas would likely vary between regions or watersheds. Most shallow slope failures occur on hillslopes in excess of about 36° (73%) and often in convergent areas (Dragovich et al., 1993). Failure on non-convergent areas occur at an even higher slope thresholds (Sekiu Watershed Analysis; Acme Watershed Analysis). In the Acme WAU (TFW Watershed Analysis, in progress), shallow failures on planar slopes typically occur on slopes in excess of 40 degrees. It is assumed for the present application that a slope threshold over which failures could be triggered by landslide debris running over the surface should have be somewhat less than 40^0. Buchanan (1988) found a failure apparently triggered by impacts by moving landslides debris on a slope of 37^0 in the Chuckanut formation. Hence, an appropriate slope threshold above which failures might be anticipated by the runout of landslide debris may be on the order of 33 to 37 degrees (65 – 75%). This value could be adjusted based on site-specific field data. Therefore, the landslide runout model described above should not be applied to hillslopes mantled by thin soils (3 to 6 feet) much in excess of 35 degrees (70%), unless site-specific data is available. Additionally, hillsides containing mature forests (including partial cuts) which provide rooting strength may be a factor in increasing the slope threshold, while clearcut slopes may cause a lowering of the slope threshold.

The landslide runout model described above does not explicity account for momentum which is based, in part, on the velocity of the landslide as it encounters a lower gradient area. It is difficult to predict or anticipate the velocity of a moving landslide thereby making estimates of landslide momentum problematic. Spreading and thinning of landslide debris as represented in the Coulomb-Viscous model allows a landslide to travel until all of the debris is deposited to some critical depth. By this approach, the model described here implicitly accounts for some degree of momentum which would cause a similar type of spreading and thinning.

The predicted range of runout distance (Figure 3) appears to be in general agreement with transport distances observed on non-convergent hillslopes (Collins et al., 1994; Fannin and Rollerson, 1993). Ideally, field data on landslide runout on non-convergent hillslopes could be used to test, and if necessary, modify the predicted runout length of landslides.

Landslide Delivery Hazards

A landslide delivery model contained within the Forest Practices Code of British Columbia (Fannin and Rollerson, 1993) has been recommended for use by the National Marine Fisheries Service (Draft Proposal on Oregon Forest Practices, February 17, 1998). The B.C. model specifies criteria for low, medium, and high hazards. The model focuses on the length of the valley floor at the base of a hillslope. Hillslopes are divided into two slope categories, less than and greater than 19°. Because no slope length is indicated, the model does not address the process of spreading, thinning, and depositing contained in the Coulomb-viscous runout model described above. Hence, landslide debris may travel over infinitely long hillslopes in the B.C. model prior to entering a valley floor. This is not in accordance with either theory or field observations of landslide debris travelling relatively short distances on non-channelized slopes because of spreading and thinning.

The Coulomb-viscous model can be used to specify relative hazards of sediment delivery to streams. Hazards can be separated into three categorizes, including high, medium, and low, similar to what has been recommended by NMFS (1988).

1) High hazard: For hillslope gradients equal to or greater than 35° (70%) assume delivery to a lower gradient area (<35°), which may include low-gradient valley floors. On slopes < 35°, slope lengths *are less* than those predicted for a high T_c (Figure 3). For example, for a 500 m^3 landslide, slope distance is less than 50 m (160').

2) Medium Hazard: For hillslope gradients less than 35° (70%) slope lengths are between the predicted runout for high and low estimates of T_c. For example, for a 500 m^3 landslide, slope distance is between 50 and 110 m (160 – 360 ft).

3) Low Hazard: For slope gradients less than 35° (70%), slope lengths are greater than the predicted runout for the lower T_c. For example, for a 500 m^3 landslide, the slope distance is greater than 110 m (360 ft).

Note, runout distances do not apply to hillslopes greater than 35° (70%) (runout is assumed because of continuous slope failures), but includes valley floors (C in Figure 4). Existence of mature forests, partial cuts, and clearcuts could be used to modify the upper slope threshold where the model can be applied. Estimates of landslide volume are needed to estimate runout in Figure 3 to determine distance categories for high, medium and low hazards. Unless information is available on landslide material properties, use estimates of T_c in Figure 1. Refer to Figure 3 on how field estimates of slope distance can be made to compare to predicted landslide runout. For runout of debris flows in confined mountain channels, see Benda and Cundy (1990).

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Benda, L. (1988) Debris flows in the Tyee Sandstone Formation of the Oregon Coast Range. MS thesis, Dept. of Geological Sciences, University of Washington. 130pp.

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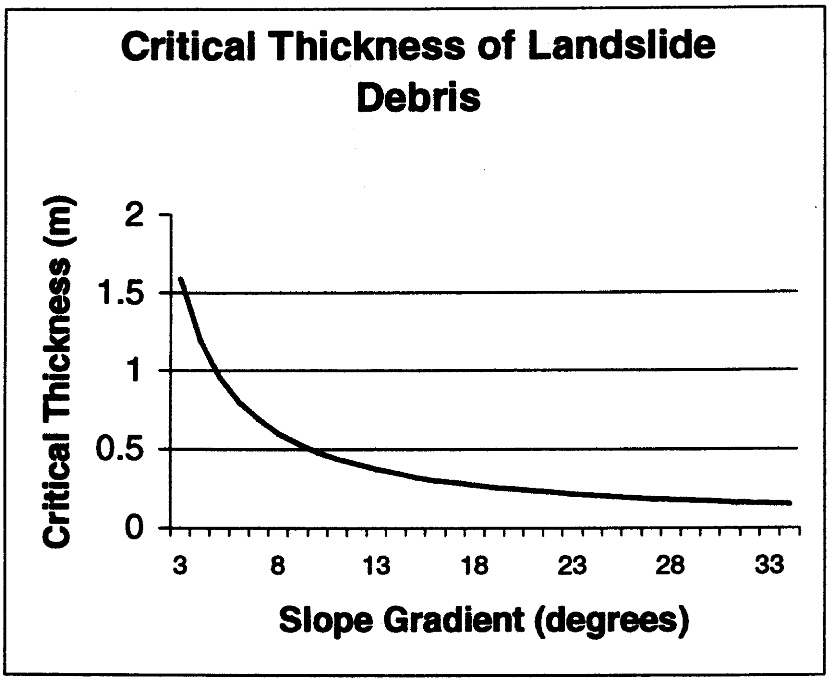


Figure 1. Critical thickness of landslide debris according to hillslope gradient based on estimates of yield strength and unit weight of material for liquified landslide debris using (1).

Geometry of Landslide Runout

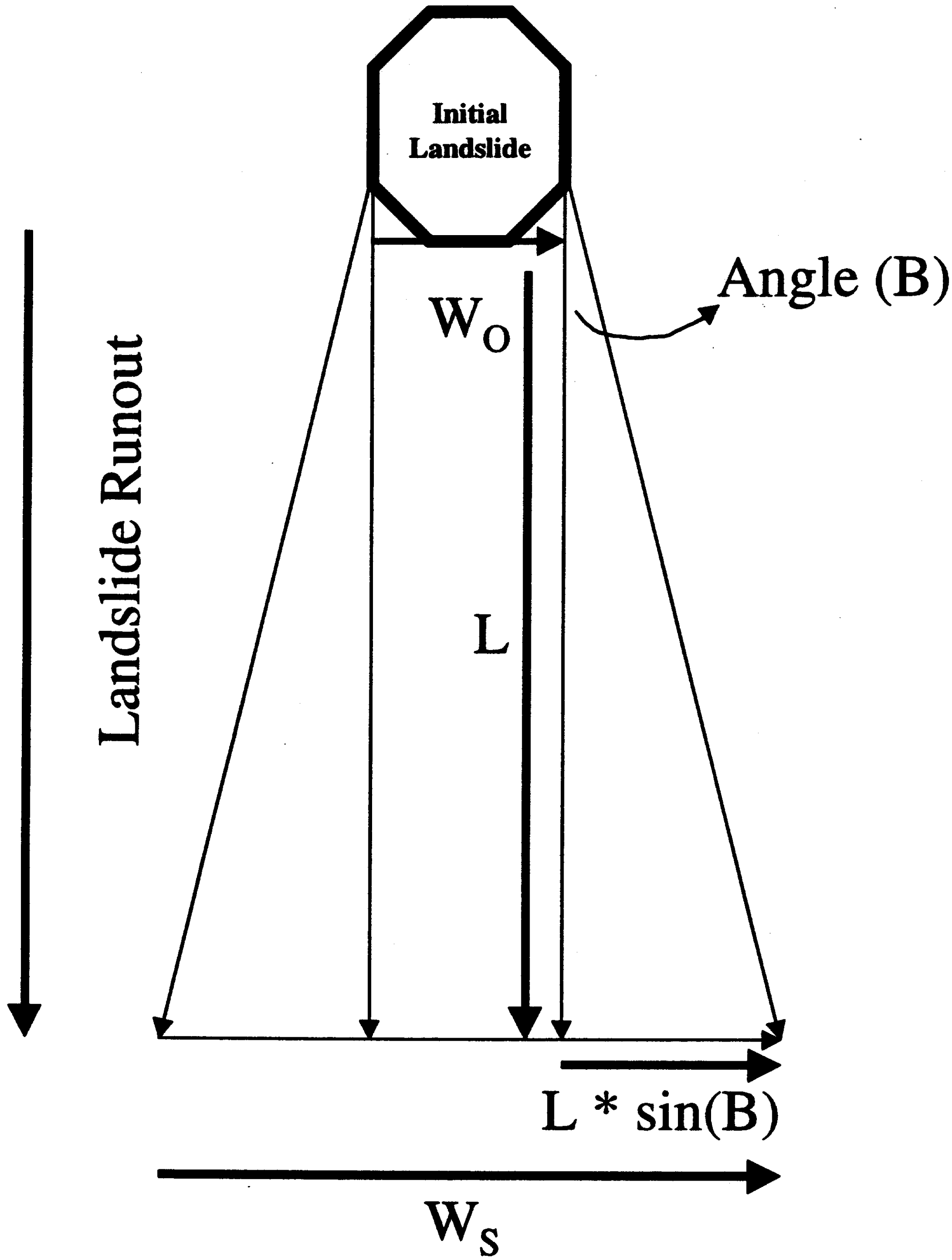
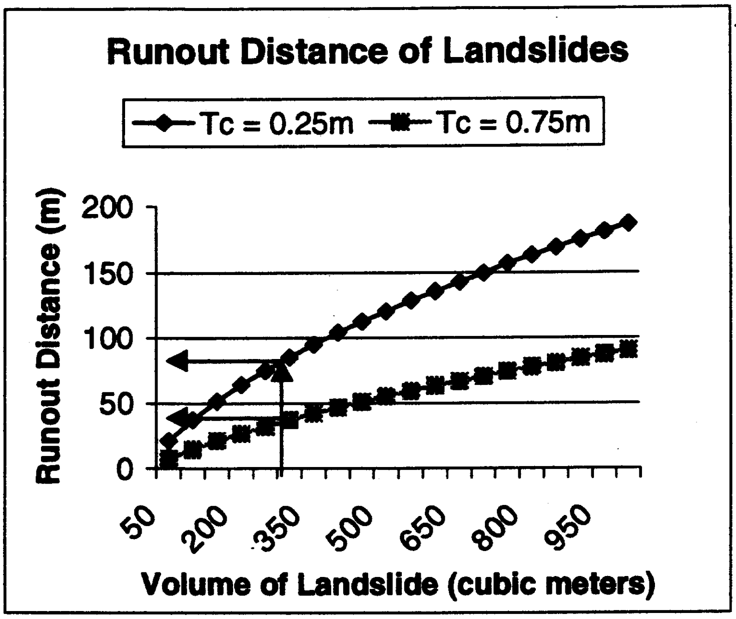


Figure 2. Idealized flow geometry of moving landslide debris on non-convergent hillslopes.



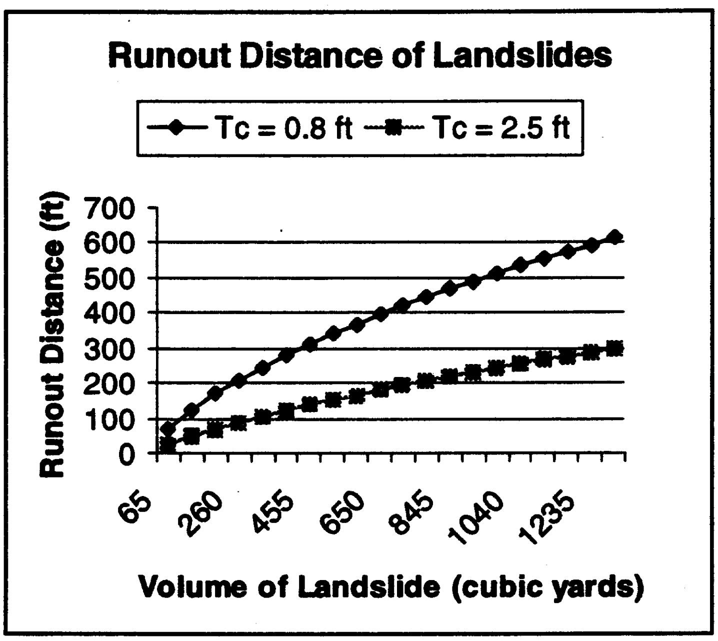


Figure 3. Predicted runout distances of landslide debris on non-convergent hillslopes less than 35 degrees (70%). Runout distance increases when critical depth of debris decreases on steep slopes (Tc = 0.25m). On lower gradient slopes where depths of landslide debris are thicker (Tc = 0.75m), runout distance will be less. The case is shown for a characteristic landslide volume of 350 m^3; runout is predicted to vary between 40 and 80 m (130 – 260 ft). Top figure in metric units bottom in English units.

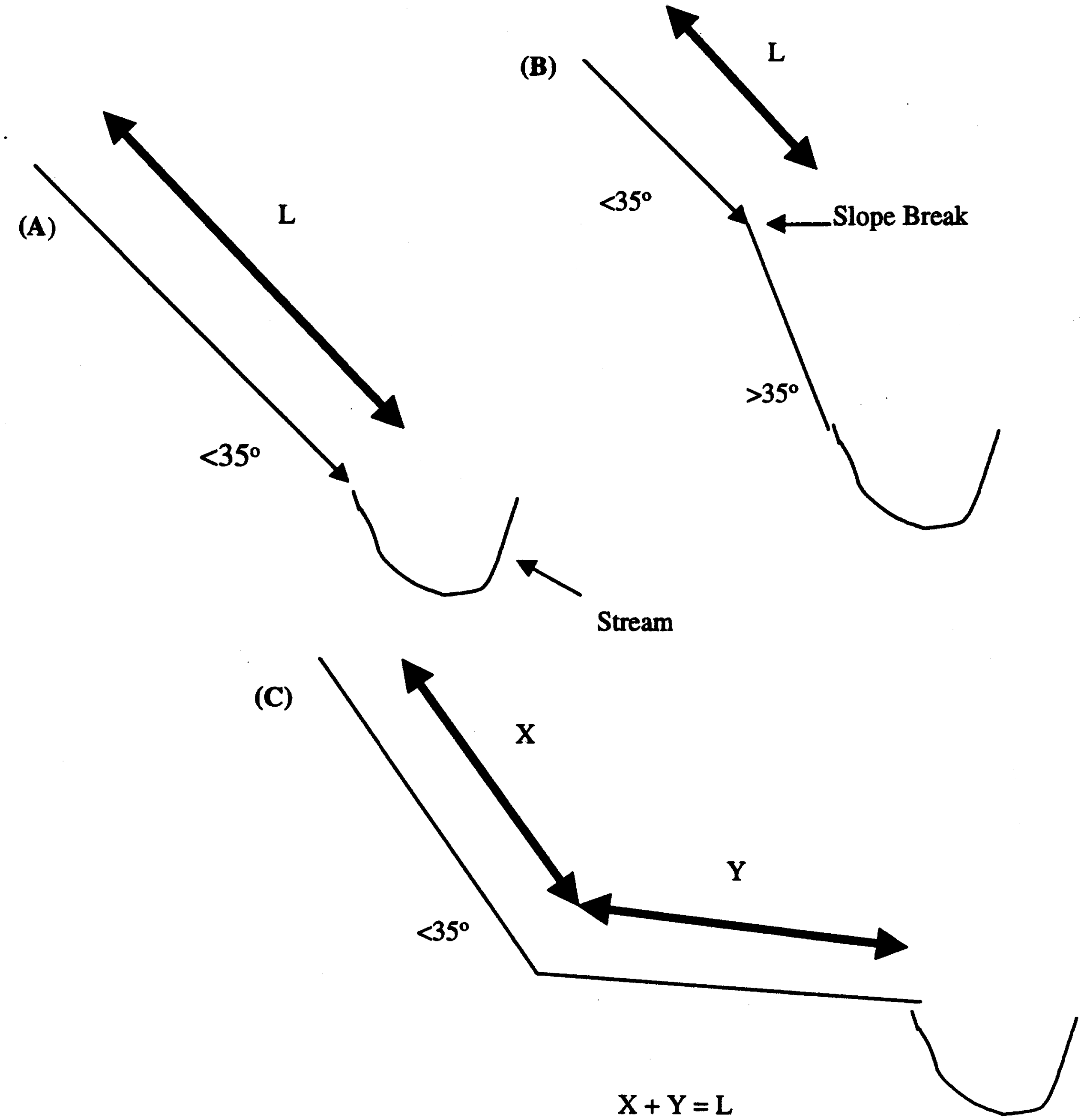


Figure 4. Slope distances estimated in the field to compare to predicted runout lengths in Figure 3. Predictions only apply to slope gradients <35° (A), hence slope distances are estimated to slope breaks (B). Relatively flat valley floors (Y) can be combined with slope length (X) to compare with runout predictions (L).

APPENDIX 11-3

Supplementary Study to the Acme Mass Wasting Assessment, Acme Watershed Analysis
August, 1998
by
Lee Benda Ph.D.

Inner Gorge Topography, Landslide Inventory, and Management Practices

Crown Pacific Corporation requested that further analysis be conducted in the Acme WAU to better define the landslide prone sites located within inner gorges and to develop a more specific classification of inner gorge topography. This information is used to recommend what, if any, management practices should be allowed in inner gorge terrain. The original definition of inner gorge topography in the Acme WAU (map unit #2) covered hillslopes greater than 36° (73%), including convergent areas (bedrock hollows), located in close proximity to stream channels of second-order and higher. It was also mentioned in the mass wasting module that inner gorges (as located on the slope stability map) may contain hillslopes between 31 and 35 degrees (60 – 72%); these were viewed as inclusions of lower hazard areas. In the module and prescriptions, the landslide potential (and hazard) associated with planar slopes greater than 36° was somewhat ambiguous and depended on a site-specific information, including locating evidence of past failures (e.g., old landslide scars, tipped and deformed trees etc.). This current analysis was primarily designed to more accurately define the hazard potential of the planar slopes in inner gorges.

The field team consisted of Lee Benda, Dave Chamberlain, Tom Smith, and Alan Soicher. Two, one-day field trips were made to the Acme WAU with most of the effort spent in the Standard Creek watershed. A total of 26 shallow landslides located in inner gorges were visited during the field trips. At each site, measurements of slope gradient, scar width, and landslide length were made. Results are plotted in Figure 1. Slope gradients of landslides ranged from 40° (84%) to 50° (119%) and averaged 44° (96%). Landslide scar widths range from 4m to 12m (13' to 40') and averaged 7.3m (24'). Length of recent landslide scars (soil exposed), which was in many cases analogous to the slope length of the inner gorge, ranged between 8m (26') to 52m (170') and averaged 22m (72'). Approximately 75% of the slides occurred in hollows with the remaining 25% located on planar slopes.

There are typically several slope breaks encountered as one approaches stream channels from upslope in the Acme WAU. The minimum slope break where all of the inventoried landslides occurred (Figure 1), including shallow slides on planar slopes, was approximately 40° (84%). Commonly, the slope break was higher, approaching 50° (119%). In addition, large bedrock hollows often extended uphill of the most landslide-prone slope break of 40°. These bedrock hollows typically were characterized by hillslope gradients in excess of 36° (73%).

Based on the field trips, the landslide inventory (Figure 1), and discussions with the four members of the field team, the following recommendations are proposed.

(1) The inner gorge landform (map unit #2), which contains both bedrock hollows and landslide-prone planar slopes, should be redefined to more accurately portray the planar slopes that are subject to failing. Inner gorges along second- and higher-order streams are redefined as the first slope break greater than 40° (> 84%) that is encountered moving away from the stream channel (e.g., 40° below the break with less steep slopes above). Limited field surveys suggest that the slope length of this inner gorge ranges between 8m (26') to 52m (170') and averages about 22m (72'). In this landform, it is recommended that no timber harvest be allowed on any slope form because of the importance of rooting strength, high delivery potential to streams, and the difficult of harvesting trees.

(2) Bedrock hollows that extend upslope from the 40° break in slope (i.e., upslope of the inner gorge, as redefined), and that are greater than or equal to 36° (73%) will continue to be considered a high hazard slope form. Existing prescriptions regarding timber harvest in bedrock hollows are unchanged. The width of the most landslide prone portion of the hollow, the area which will contain leave trees, will need to be defined in the field or based on the slide inventory (Figure 1). Characteristic widths of shallow failures obtained during the field inventory ranged from 4m (13') to 12m (40') and averaged 7.3m (24'). These widths are similar to those measured by Buchanan (1983) of 4 to 10 m (12 to 33'). In addition, the width of the buffer should account for any tree roots that intersect the perimeter of the failure plane (Figure 2).

(3) Planar and divergent slopes are referred to as non convergent hillslopes. On non convergent hillslopes between 36 and 40 degrees (73 – 84%), in the absence of field evidence for landsliding, it is recommended that clearcutting be considered. In addition to old (revegetated) or recent landslide scars which would provide evidence for failure on non convergent slopes, "discontinuity surfaces" and "wedges" could be used as a field indicator of potential instability. In a study of landsliding on the Chuckanut sandstone formation, Buchanan (1988) identified the landslide potential of discontinuity surfaces, defined as steep, planar sandstone surfaces (containing no fissures or fractures and therefore not penetrated by tree roots). In most cases, discontinuities involve bedding surfaces that dip downslope but they can also be exfoliation joints in massive sandstone beds (Buchanan, 1988). In the field, discontinuities are identified by abrupt and steep temporary breaks in slope, characterized by thin soil or soil-free bedrock areas. Landslide debris (hummocky ground) may be located below the break in slope (Figure 3). Buchanan also identified failure potential of wedges, which are small pockets of soil located in shallow convergent areas often at heads of first-order or type 5 streams. It is recommended that timber harvest not be allowed on such landslide-prone sites.

On non convergent slopes between 36 and 40 degrees, partial cutting may be employed as a strategy to reduce perceived landslide risk and delivery to streams, particularly when differences of opinion occur. For example, at times there may exist disagreement regarding the existence or location of landslide-prone areas, such as discontinuity surfaces or wedges in certain areas. Partial cutting in these areas may provide a means to reconcile differences in perceptions of landslide risk and delivery of material to streams. In addition, partial cutting may be a strategy to reduce the delivered hazard *rating* from high to moderate, or from moderate to low (refer to Crown delivery rules, in preparation). In this latter context, partial cutting on non convergent 36 – 40 degree slopes could potentially be used to provide some flexibility in laying out timber harvest units involving landslide-prone areas, including perhaps placement of logging roads and creation of yarding corridors. The width, or slope length, of such a partial cut prescription could be defined by Crown Pacific landslide delivery rules (likely on the order of several hundred feet, see Benda, 1998).

(4) Blowdown was observed at two recently-created inner gorge buffer areas in the Acme WAU. It appeared that small patches of blowdown triggered landslides which delivered sediment and woody debris to channels. Debris flows or dam-break floods in the small mountain streams were not triggered. In general, the steep, mountain channels are sediment limited (many reaches floored with bedrock) and they contain low volumes of large woody debris. At least at one site, the large wood appeared to be creating pool habitat and storing sediment.

Blowdown of inner gorge buffer strips was discussed in the field. Several options were reviewed by team members. A consensus was not reached but a list of issues was developed and recommended to guide discussions of inner gorge blowdown by an expanded group of analysts, including additional members from Crown Pacific, private consultants, and Department of Natural Resources.

<u>Blowdown Issues:</u>
1) Blowdown of inner gorge buffer strips is a likely occurrence, depending on topography of the site and forest (buffer) characteristics in the Acme WAU.

2) Landslides in inner gorges can degrade water quality. Depending upon location, landslides may trigger dam-break floods which may impact fans.

3) Blowdown can trigger landslides which deliver sediment and large wood to streams. Some of this material may create aquatic habitats for years to decades.

4) Environmental impacts from blowdown-related landslides, or the habitat aspects of such slides, depend on their frequency and spatial distribution across the landscape. A lower spatial occurrence of these types of failures is perceived as less of an issue compared to a higher spatial frequency.

5) Harvest trees over the break of slope to reduce sail area and reduce blowdown-related failures. However, reduced rooting strength may also contribute to failure in the inner gorge.

6) Prune tree tops to reduce sail area while maintaining tree root strength.

7) Increase buffer width over the break in slope to reduce blowdown.

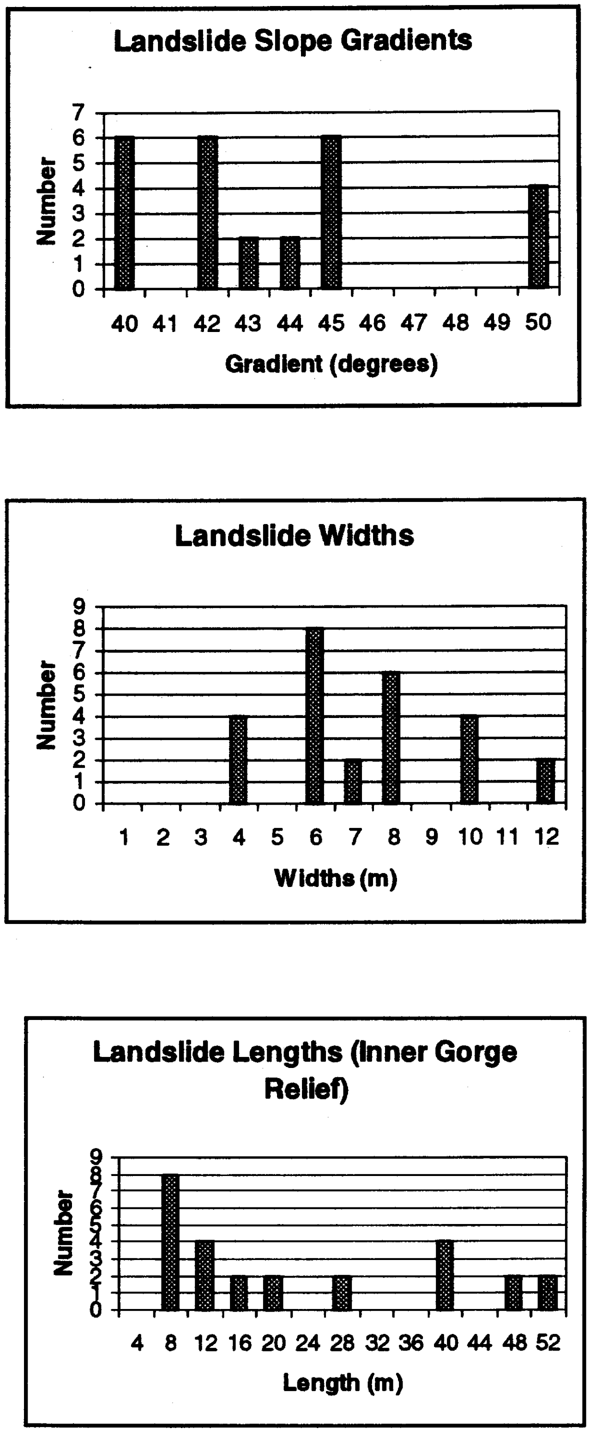


Figure 1. Distributions of hillslope gradients, widths, and lengths of shallow landslides located in inner gorges in the Acme WAU. Measurements of landslide lengths are approximately equivalent to the height of the inner gorge landform.

Bedrock Hollow

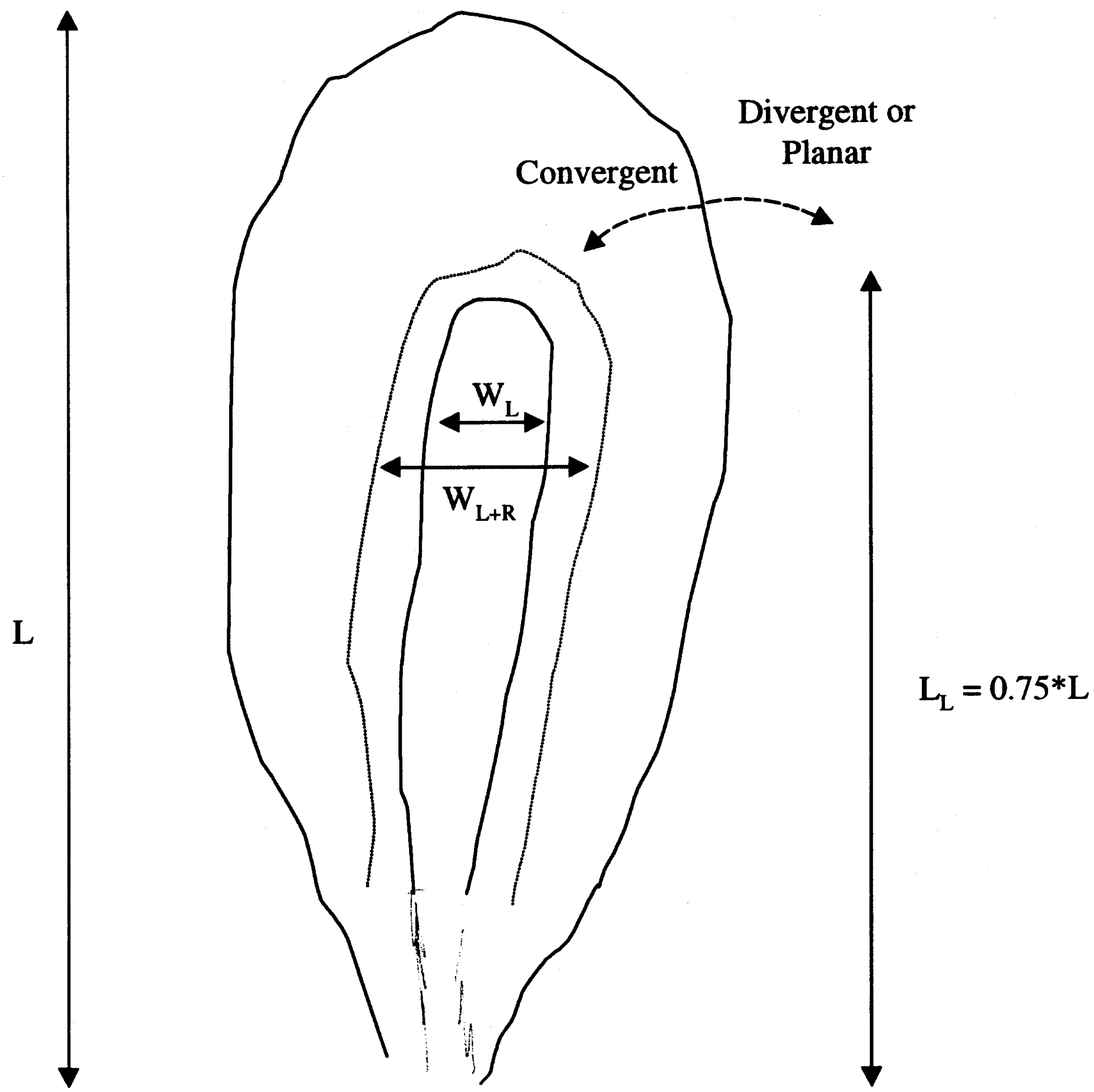


Figure 2. Potential buffer areas in bedrock hollows (does not apply to inner gorges (>40^0)). W_L refers to the characteristic width of a landslide scar, either 24' (Figure 1) or based on site specific field evidence. W_{L+R} refers to the width of the characteristic scar plus a band approximately 15' wide that surrounds the perimeter of the scar that accounts for tree roots intersecting the failure plane. L_L is three quarters of the length of the hollow (L).

Potential Landslide Site on Planar Slopes

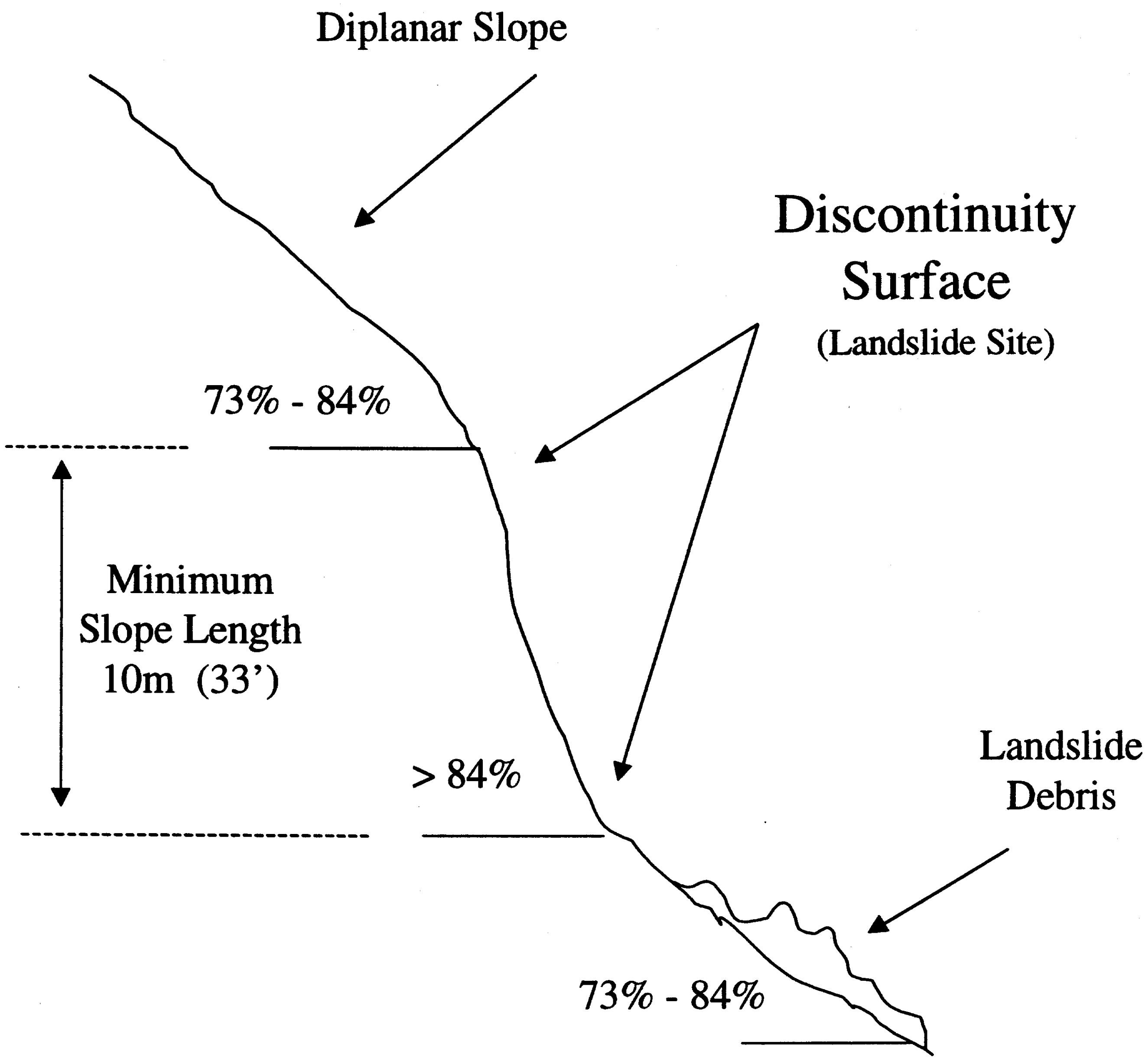


Figure 3. Sketch of a landslide-prone discontinuity surface.

APPENDIX 11-4

Evaluation of fall 1998 windthrow in slope stability leave areas at the Jones Creek and Hardscrabble harvest units

January 27, 1999

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Evaluation of fall 1998 windthrow in slope stability leave areas at the Jones Creek and Hardscrabble harvest units

INTRODUCTION

On December 18, 1998, forest hydrologist Curt Veldhuisen and Dave Chamberlain of Crown Pacific visited two sites near Acme where significant windthrow had occurred in leave areas adjacent to recent clearcuts. At both locations, windthrow occurred in forest leave areas designed to mitigate timber harvest impacts to slope instability. The two harvest units involved are known as "Jones Creek", located in Section 12 of T. 37 N., R. 4 E. W.M., and "Hardscrabble", located three miles north in Section 25 of T. 38 N. R 4 E. Both units are within the Acme Watershed Administrative Unit, the subject of a nearly completed Watershed Analysis (Crown Pacific 1998). The units were laid out in early 1998 to comply with interim Acme prescriptions at that time and were logged in mid-1998.

Following the field visit, Curt Veldhuisen was requested to provide a report that would:

1. Assess the impact to leave areas resulting from the windthrow,
2. Determine the extent that leave area functions had been impacted, and
3. Provide commentary on strategies for minimizing windthrow impacts in the Acme area.

The nature of the windthrow and its functional impact (#1 & 2 above) are discussed separately for each site in the "Observations and Analysis" section below, while issues of windthrow management (#3 above) are addressed in the final section: "Comments on windthrow management in the Acme WAU".

THE FALL 1998 WINDSTORMS

We could not determine precisely when any of the windthrow occurred, as northwest Washington received numerous episodes of strong winds during November and early December of 1998. Windy periods were associated with typical late fall cyclonic storms approaching from the Pacific Ocean, which bring mild temperatures, rainfall, and gusty winds from the south and/or southeast. Northwest Washington experienced several such windstorms during the week prior to Thanksgiving 1998, the strongest on the night of November 23rd & 24th. Due to the rainy conditions prevalent during prior weeks, soil moisture levels would have been relatively high which would have reduced soil strength.

The extent of windthrow from the fall 1998 windstorms was sizeable and dispersed throughout managed forests of northwest Washington (Noel Wolff, DNR soil scientist, personal communication on January 4 1998), indicating a fairly widespread impact. The regionally consistent orientation among wind-thrown trees indicates that the strongest winds were from the south in most locations. Noel Wolff estimates that the scale of windthrow from the fall 1998 storms was considerably greater than that from any during fall/winter 1997/98, though less than what occurred in the winters of 1995/96 and 1996/97. Judging from these comparisons, the intensity of the fall 1998 windstorms was substantial, though apparently not of an exceptional or catastrophic magnitude. Despite the limitations of inferring wind velocities from subjective observations, direct analysis of local wind-speeds would be unreliable, since wind data are not collected at any comparable Cascade foothill location.

Due to the north-south orientation of the South Fork Nooksack valley, winds from the south and southeast tend to be channeled down the valley. As a result, hillslopes exposed to down-valley winds are relatively wind-prone, in contrast to the valleys of the primary tributaries (Jones, Standard, Hardscrabble, etc.) and other incised terrain. The South Fork valley is less subject to the northeasterly Fraser-outflow winds that impact northwestern Whatcom County.

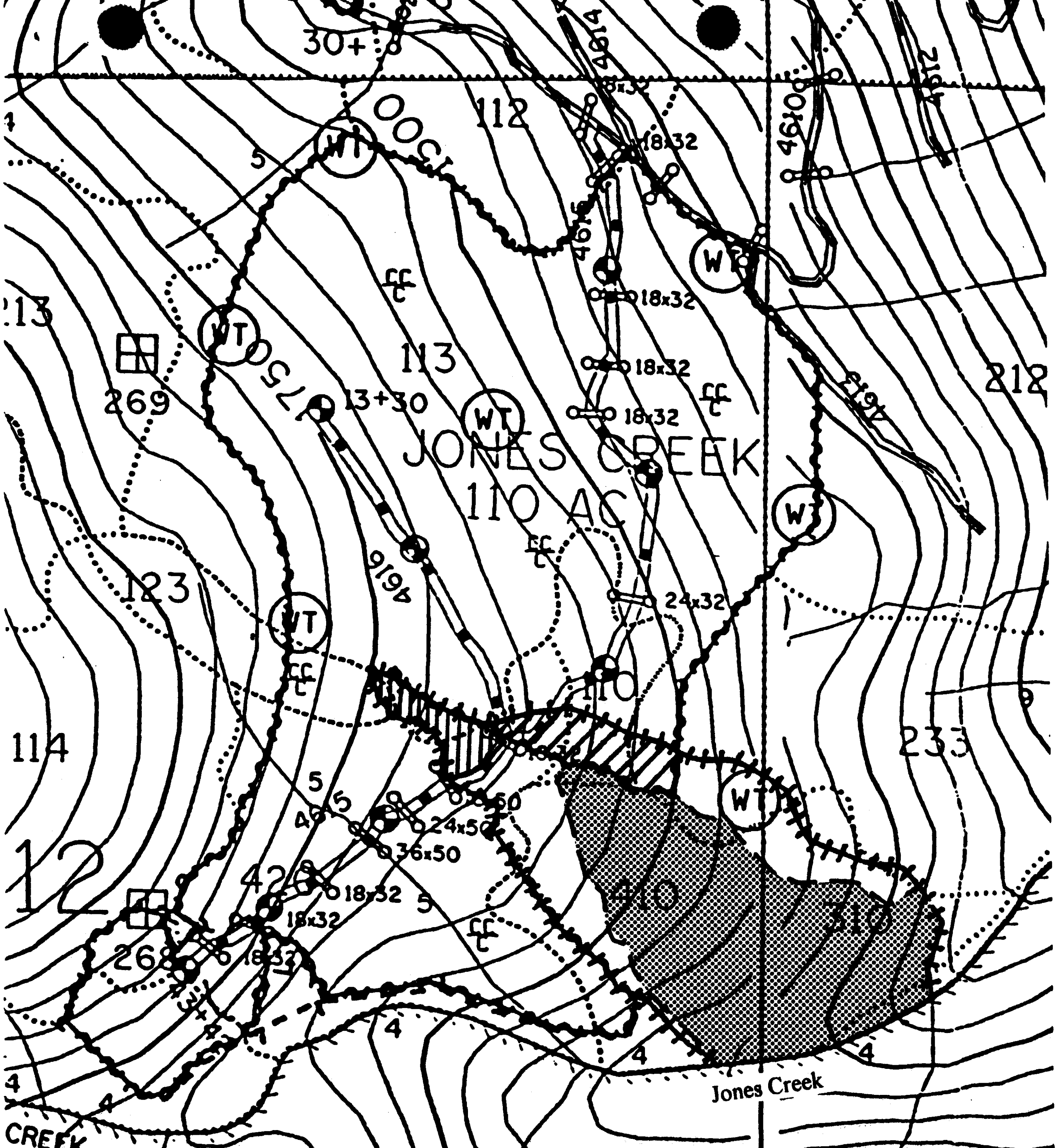
OBSERVATIONS AND ANALYSIS – JONES CREEK UNIT

Setting: The Jones Creek Unit is located on moderately sloping terrain north of Jones Creek (Map 1). The geology consists of Darrington phyllite (Easterbrook 1971) overlain by moderately deep (3-5 feet) colluvial soils derived from weathered phyllite and volcanic ash. Prior to logging, the forest type throughout the Jones Creek Unit and vicinity was second-growth conifer and alder with some concentrations of older residual conifers. Stand densities are/were moderate to high.

Intended Function: Recent windthrow impacted the narrow upslope end of a leave area designed to mitigate potential hydrologic harvest effects to a large active deep-seated landslide located southeast of the unit (Map 1). The trees blown down were not on the landslide itself but rather on part of the so-called "Groundwater Recharge Zone" (or GRZ). Retention of partial forest cover over the GRZ was prescribed to limit post-logging increases in soil moisture due to reduced evapo-transpiration (Crown Pacific 1998, Prescriptions). Additional soil moisture from canopy removal on the GRZ would be expected to travel into the active landslide mass via subsurface flow, thus potentially contributing to accelerated slide activity. Providing evapo-transpiration is the only function of trees left on the GRZ and rooting strength is of no functional importance.

The requirements for mitigating harvest impacts to active deep-seated landslides in phyllite, such as this, were specified in the prescription for Mass Masting Map Unit (MWMU) #9 in the Acme interim prescriptions (Crown Pacific 1998). Once this landslide was identified, Curt Veldhuisen was hired to confirm its status as MWMU #9 and then mark the boundaries of both the active slide area (i.e. MWMU #9) and the associated GRZ for the purpose of harvest planning. Prescriptions required that the landowner (Crown) retain mature timber over the active slide (which is mostly forested) and a portion of the GRZ equivalent to 50% of the area of the active landslide. Prescriptions allowed the landowner to choose the portion of the GRZ to remain forested.

Impacts and Discussion: Recent windthrow was concentrated at the eastern or upslope tip of the GRZ, where the leave area width narrows (Map 1). Within the 1.7-acre portion of the GRZ located above the newly constructed road, approximately 70% of the trees were uprooted, which is equivalent to 1.2 acres of lost forest canopy. Most of the trees that remained standing are located closer to the road and windthrow elsewhere in the GRZ appeared to be minimal. From the perspective of the prescription requirements, the recent windthrow has reduced the forested portion of the GRZ from 9.2 acres (51% relative to active portion) after logging to 8.0 acres (44%).



Map 1 –
Jones Creek Unit

Logging unit boundary

Active deep-seated lands

Groundwater recharge zo
(GRZ) boundary

Portion of GRZ logged

Portion of GRZ impacted
by fall 1998 windthrow

N

Approximate scale:
1" = 500'

CNV 1-8-99

The functional importance of the windthrow is that increased moisture inputs will occur over a somewhat larger proportion of GRZ than had been planned. Because the per-acre effects of windthrow and logging on evapo-transpiration would be similar, the magnitude of additional moisture inputs can be calculated on the basis of the additional canopy loss. The results of this analysis are summarized in Table 1, with the calculations and supporting assumptions provided in Appendix 1. These estimates reflect the effects of logging and windthrow on the total soil moisture inputs to the landslide, and thus integrate the effects of forested and non-forested portions of the active slide area and GRZ by means of generating area-weighted averages.

Table 1. Effects of logging and windthrow on total soil moisture input to the deep-seated landslide southeast of the Jones Creek Unit. Values pertain to estimates for the total acreage contributing soil moisture to the slide, i.e. the combined areas of the landslide and Groundwater Recharge Zone. See Appendix 1 for supporting calculations.

Condition	Hydrologically immature area (% of total)	Annual soil moisture input* (area-inches)	Increased soil moisture input compared to pre-logging (%)
Pre-logging	0%	39"	----
Post-logging	8%	40.5"	+4%
Post-windthrow	12%	41.3"	+6%

* - Annual soil moisture inputs will fluctuate considerably around this average due to year-to year variability in total precipitation and other climatic conditions. Input values for specific years will commonly deviate 2-5 inches from these values in either direction.

In comparison to fully forested conditions, the 2.4 acres of GRZ harvest increased the total moisture input by 4%, while the windthrow produced an additional 2% for a combined increase of 6%. Based on the general observation that greater moisture inputs contribute to greater movement of deep-seated landslides, this increase could contribute to greater slide activity. Whether this landslide will respond to soil moisture increases of this scale remains uncertain, as the sensitivity among individual deep-seated landslides to timber harvest is notably inconsistent and many show no response to equivalent or greater harvest effects.

It should be noted that increases in soil moisture input of 2% to 6% (1.5-2.3 inches) would be considerably smaller than fluctuations in moisture inputs this slide commonly experiences due to seasonal and year-to-year differences in precipitation and evapo-transpiration. For example, an effort to model rates of groundwater recharge in a similar climate produced year-to-year differences of $\pm$ 10 to 50% (or 4 to 8 inches, per Miller and Sias 1997). Still, the effect of partial forest removal from the GRZ is equivalent to a series of slightly wetter years over the next 20 to 30 years until the new vegetation is sufficiently developed to provide pre-harvest rates of evapo-transpiration.

Because the wind-thrown trees no longer provide evapo-transpiration, recovery of hydrologic functions depends upon the growth rates of new plant cover. To this end, any timber salvage operations should avoid damage to remaining trees and understory vegetation and avoid soil disturbance. Because tree limbs and needles can provide much of the interception capacity of standing trees, retention of slash within the GRZ will provide partial interception function. To accelerate the recovery to full evapo-transpiration rates, the wind-thrown area and logged portions of the GRZ should be promptly reforested with conifers.

OBSERVATIONS AND ANALYSIS – HARDSCRABBLE UNIT

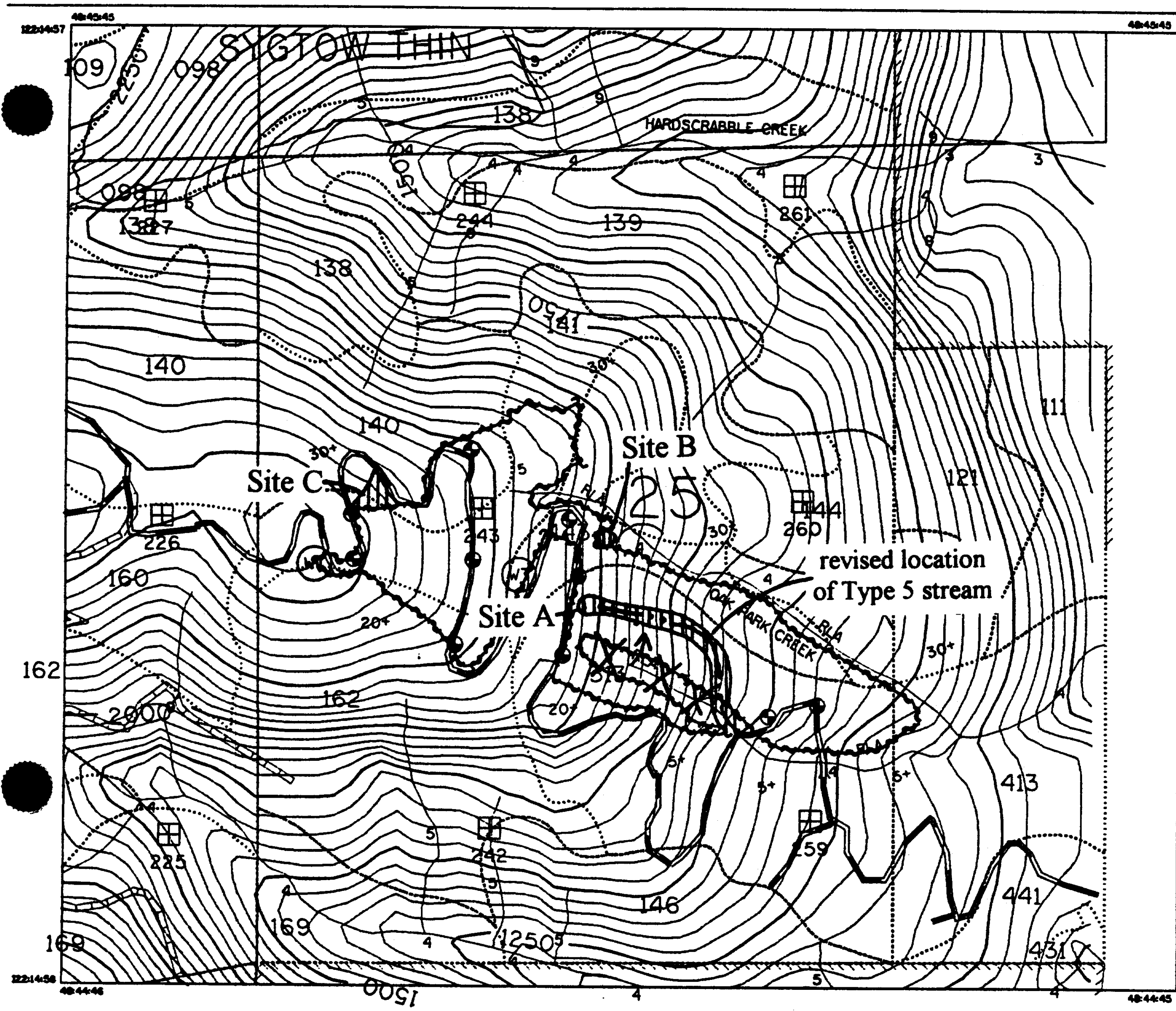
Setting: The Hardscrabble unit is on steeper terrain situated on the broad end of a spur ridge that extends east from the main crest of Stewart Mountain (Map 2). Geologic conditions differ from the Jones Creek unit in that the Hardscrabble unit is underlain by sedimentary rocks of the Chuckanut Formation, consisting here primarily of massive sandstone beds. Soils are generally thin (1–3 feet), sandy, and well drained. The stand type prior to harvest was a relatively dense second-growth mixed-conifer forest (Douglas-fir, hemlock and cedar).

Substantial windthrow was observed at three separate locations at the Hardscrabble unit, shown approximately on Map 2. The first location, "Site A", involves a linear leave area through the center of the lower clearcut unit that was mostly blown down. The second ("Site B") involves a pocket of timber along the unit boundary north of Site A, while the third ("Site C") occurred along the northern cutting boundary near the northwest corner of the Hardscrabble unit.

Intended Function: Windthrow trees at Sites A and B had been left to mitigate the hazard of increased shallow rapid landsliding. The primary intended function of leave trees was retention of rooting strength; secondary functions were to avoid increases in soil moisture inputs during rain-on-snow and to prevent soil disturbance from log yarding (Crown Pacific 1998, Prescriptions). Although the cutting boundary at Site C was placed for timber management rather than slope stability objectives, windthrow observations may be relevant to broader questions of windthrow management. Further discussion of local conditions and impacts is presented below on a site-by-site basis.

Site A – Linear leave area

Impacts and Discussion: The linear leave area at Site A covers a steep bedrock hollow located a short distance below the access road and continues along a Type 5 stream to the southern unit boundary (Map 2). The hollow is relatively small, but quite steep (~35-40°) and contains the channel head of the Type 5 stream near the bottom. The Type 5 stream flows through a small inner gorge (~30-40 feet of relief) with locally steep slopes (35-40°). The no-cut leave area was laid out to cover hollow and inner gorge slopes that exceed 35°, resulting in a total width of approximately 30-75 feet (Dave Chamberlain, personal communication). Because location of the Type 5 stream as displayed on the original map was somewhat inaccurate, it was redrawn on Map 2 included here.



Hardscrabble

Map 2 – Hardscrabble Unit

Map Type:FPA
County:Whatcom

Section 25, Township 38 North, Range 4 East

Prepared By:D. Chamberlain
Date:5-18-98
Scale: 1" = 1000'

Lines:

TOWNSHIP
OWNER
INACT-RD
NON-DRIV
FORES-RD
FOR-INV
STREAM
HARVUNIT

Symbols:

GTWT
Bridge - Perm
Landing - Prop

Windthrow areas

N

Crown Pacific

Remark:

The great majority of trees within this leave area (estimated 90%) were blown over during the November storms. Most trees fell with their root-wads intact, revealing shallow, plate-like root masses, which had been unable to penetrate into the sandstone. The few standing trees are generally Douglas-firs that have lost much of their crown and/or had cracked the soil around their root masses during swaying and may yet fall. Given the steep and sandy soils, excessive soil moisture was probably not a major factor in the uprooting, except perhaps at the center of the hollow near the channel head. All trees were blown northward, confirming the southerly orientation of winds at this location. Stems of nearly all the trees that had been rooted south of the stream lie nearly perpendicular across the channel or hollow and may provide barrier functions (more below).

Assessing the importance of this windthrow to slope instability requires consideration of several functions of these trees, whether standing or fallen. It is clear that the uprooting of most trees resulted in a near-total loss of rooting strength, which was the stated objective of this leave area (Crown Pacific 1998, Prescriptions). In addition, because most roots were pulled, there is no residual rooting strength as would occur following logging. Though soil disturbance from uprooting was considerable, this is not expected to affect soil stability. A lesser concern is that any mitigating effects these trees had upon rain-on-snow have been lost as well. In summary, it appears that the probability of a shallow failure in the hollow and/or inner gorge has increased, largely due to the loss of rooting strength.

One unintended consequence of this windthrow is the abundance of down trees that would provide barrier effects. The ability of standing or fallen trees along a channel to impede or reduce momentum of debris flows has been widely observed but is not yet well understood (Benda et al. 1997). More important in assessing the influence of windthrow is the relative degree of barrier effect provided by standing vs. spanning down trees, which is also unknown. Calculation of the forces involved indicates, however, that barrier trees are most likely to halt a debris flow when they are encountered quite near the landslide initiation point before much momentum has been gained (Coho and Burges 1994). Once a debris flow that has traveled any considerable distance, either standing or spanning trees in its path are likely to be overwhelmed and entrained into the moving debris.

Given the importance of proximity to the initiation point, the wind-thrown trees at Site A are well situated to prevent debris flow propagation, as they are distributed along the entire length of the unstable terrain. The fallen trees that are most likely to preclude debris flow initiation are those lying across the bedrock hollow or shortly downstream, as they are closest to the most likely origin of instability. Most spanning trees are 12-20 inches in diameter and are buttressed against other fallen trees or stumps, contributing to their stability. It appears unlikely that a small failure would generate sufficient force to break through or displace all the fallen trees, as would be necessary for downstream propagation. The mechanical strength of uprooted trees will decline over time with decay, but should be substantial for at least 1-2 decades, roughly the amount of time required for new vegetation to develop rooting strength. Trees that fell away from the channel provide minimal barrier function, except those that buttress other trees that span the channel.

In summary, the probability of a shallow failure has increased due the loss of rooting strength from wind-thrown trees. Fine sediment from such failures and surface erosion of uprooted soil could contribute to turbidity downstream. However, unless spanning trees are removed, the likelihood of a debris flow that would propagate downstream appears fairly remote due to the abundant spanning barrier trees. Perhaps the most likely scenario for initiation of a landslide large enough to break or entrain the fallen trees would be a failure originating at the road above. Although this segment of road appears to have been properly constructed, ongoing attention to shoulder stability and drainage maintenance will be of particular importance here. In addition, trees should be planted within the wind-thrown leave area as soon as practical. One alternative plan for this site would be to interplant Douglas-fir with a less windthrow-prone species, such as bigleaf maple. Further considerations relevant to this mixed-species strategy are explored in the final section.

Site B – North Unit boundary

Impact and Discussion: The wind-thrown trees at Site B were growing in shallow soils along the clearcut boundary. The cutting line was placed around this feature due to the steep slope (~42°), slightly concave slope form, channel head, and continuously steep slope below. The cluster of trees that overturned were rooted in shallow soil (12-18") over unfractured sandstone, and roots had intertwined into a mat-like structure. The interlocking root structure explains why the entire group of trees appeared to have fallen together at once. The wind-thrown trees lie in a pile at the base of the exposed slab, with their crowns oriented toward the northwest. The orientation of the crowns downwind, rather than upslope, suggests that wind-generated stress on the crowns was the primary triggering force, rather than soil failure from beneath. The concave bedrock surface concentrates subsurface flow and abundant soil moisture probably contributed by weakening the adhesion at the soil-rock interface at this location. Of the soil enmeshed in the roots, some of the finer particles would have been washed downstream during subsequent rains.

Because the entire soil layer was removed from the center of the bedrock hollow, the potential for further failure from the steepest area has been virtually eliminated. There remains a possibility that the soil located directly above could still fail, though the slope gradient is considerably less. The wind-thrown trees lie across the travel path of any subsequent failure and thus could provide barrier functions, as was described for Site A. Though the hillslope below is continuously steep, it remains forested with mature conifer trees that would provide pre-windthrow levels of resistance to any landslide originating near the recent windthrow.

To conclude, the risk of shallow failure may have increased slightly, due to the loss of a continuous root mat across the hollow. The scale of impact from this windthrow appears to be relatively slight, because only a small cluster of trees was affected and the uprooting removed all soil from the steepest portion of the hollow. At this point, I would not recommend salvaging the windthrown trees because: 1) they provide barrier functions that may block material from any further instability, and 2) extraction of the fallen trees would be difficult without disturbing remaining trees and soil around the margin of the windthrow area. Successful reforestation of logged areas surrounding this site will contribute to a long-term increase in site stability. As at Site A, the greatest risk for landslide initiation would involve the road above, if drainage water were routed into this area, due to a ditch malfunction.

Site C – Northwest Unit boundary

Impact and Discussion: The substantial windthrow at Site C occurred along the northwest cutting boundary (Map 2). The timber edge was oriented up-and-down the ridge crest, which is rounded and does not provide an obvious topographic break. Because there was no unstable terrain to constrain this boundary location, it was chosen for timber management objectives. Although the windthrow at Site C is of no consequence to slope instability, the timing and scale of windthrow here is pertinent to broader discussions of windthrow management.

Although the majority of windthrow here occurred during the large windstorms of late November 1998, additional windthrow continued through subsequent storms. By late December, windthrow had extended approximately 240 feet downwind into the uncut stand (Dave Chamberlain, personal communication). This process is termed "progressive" windthrow, when windthrow of the most exposed trees allows greater exposure of the trees that had been sheltered behind them, which then fall, exposing others downwind, and so on. As occurred here, progressive windthrow can result from a series of windstorms and/or a single storm with longer periods of sustained high-velocity winds (Stathers et al. 1994). Over a period of years, progressive windthrow may continue into the windward stand until some type of topographic wind protection is encountered. This local evidence of progressive windthrow illustrates the major drawback to the strategy of leaving additional trees on the windward side of an unstable area for the purpose of shielding the unstable portion, a strategy discussed further in the following section.

COMMENTS ON WINDTHROW MANAGEMENT IN THE ACME WAU

The recent windthrow at the Jones Creek and Hardscrabble Units follows two other previous windthrow events encountered in the vicinity (e.g. Trillium "Spar Tree" unit, and an older DNR unit in the NE corner Section 36). Each of the prior two windthrow events involved a patch of tall conifers rooted just below the upper edge of an inner gorge, but whose crowns were exposed to southerly winds. The fact that the triggering winds were not of exceptional force suggests that winds of similar magnitude could be expected every several years or so. Taken together, these events suggest that windthrow of this scale will be an ongoing occurrence on eastern Stewart Mountain, where many intricate leave areas are being created across a highly dissected landscape.

But, even when taken together, the combined area affected by these windthrow events comprises only a small percentage out of the many sizable leave areas created in the past several years. Despite the value of evaluating individual windthrow events, such as was done here, findings are inadequate to determine the overall scale of windthrow across the landscape. Wider-scale information must be collected from all leave areas, including those where no windthrow has occurred, in order to allow any interpretation of the overall scale and severity.

Although the ecological implications of windthrow in leave areas are complex, some generalizations can be made from the four events mentioned above. Because wind-thrown trees have tended to pull out the majority of their root mass, the typical result is a near-total loss of rooting strength in the immediate area. In most cases locally, some fine sediment has been delivered to the stream channel, though a broader study found that sediment input volumes associated with most instances of riparian windthrow were minimal (Grizzel and Wolff 1998).

However, when windthrow does deliver soil, it also brings in tree stems as well, which contribute sediment trapping and habitat. There are no recent examples of harvest-related windthrow triggering long-runout debris flows of the type that has created the most extensive resource damage in the area (Crown Pacific 1998: Mass Wasting Assessment), though debris flow initiation would be possible under certain conditions. Given these factors and many secondary ecological effects not discussed here, the net response includes both positive and negative considerations, locally and downstream. Windthrow in portions of leave areas is certainly preferable to the typical outcome of clearcutting such unstable slopes: i.e. increased landsliding five to fifteen years later, but without the contribution of woody debris.

Given these generalities, the success at mitigating windthrow impacts depends on three issues:

1) Whether windthrow (either partial or widespread) would substantially reduce the function of any particular leave area,
2) Whether certain topographic attributes that define hillslopes suseptible to windthrow can be accurately identified, and
3) Whether leave area design or edge treatment strategies can be refined that will allow reasonable operational flexibility while maintaining resource protection functions.

Impact assessment (Item #1) will be difficult for leave areas designed to provide more than one function. Hardscrabble Site A, described above, provides an example of a leave area designed to prevent debris flows by providing rooting strength and canopy coverage, though barrier effects provided by fallen trees may have a similar effect achieved via an unintended function. Another case would be a riparian buffer designed to provide woody debris and shade; blown-down trees would provide the wood, but unavoidably reduce the shade. In this case, impact might depend on the how much, if any, shade loss could be accepted without exceeding desired stream temperatures.

Predicting windthrow susceptibility (Item #2 above) would be critical for managing any area where functions depend on standing trees. One approach would be to test the windthrow handbook developed for British Columbia (Stathers et al. 1994) as a tool for hazard evaluation. Although this book appears to be a valuable resource, using it for regulatory purposes would be difficult, since the rating system is qualitative, and as the book's preface states: "It is not a rule book" (Stathers et al. 1994). A broader inventory of windthrow from the Acme WAU would be highly valuable for validating or even modifying this or other hazard rating systems used elsewhere. Even the few local windthrow events in the Acme area provide at least one promising generalization: Windthrow has generally been restricted to windward east-west cutting boundaries hit directly by southerly winds, at locations where any topographic protection to the south was inadequate to shelter the taller crowns. In contrast, cutting lines on slope breaks located in the deeper valleys have not been greatly effected.

Implementation of windthrow treatments (i.e. Item #3 above) will largely depend on the ability to define those sites where the trees that provide critical functions are highly susceptible to wind. If such sites can be identified with confidence, this would focus specialized practices on limited number of sites. In contrast, if critical windthrow areas are found to be broadly distributed and/or hard to identify, use of experimental practices is more cumbersome. Finding a suitable treatment for bedrock hollows on exposed slopes, such as Hardscrabble Site A will be particularly difficult because the hollows are not nearly deep enough to provide shelter to even the lowest crowns of mature trees.

With these uncertainties in mind, three possible approaches to windthrow bear consideration:

1. **Leave additional wind buffers of standing trees outside the windward edges of unstable leave areas**. This could likely reduce the extent of windthrow in some critical areas, though the most exposed locations would remain vulnerable via progressive windthrow, as seen at Hardscrabble Site C. This approach results in the greatest timber loss to landowners, but may be justified where downstream risk to public resources is greatest.

2. **Leave timber on unstable areas only and accept the occurrence of some blowdown.** The major advantage to this approach is that harvest boundaries would generally be placed along topographic breaks, which provide natural wind protection, at least for trees below the exposed edge. This approach would be reasonable for sites where windthrow would not substantially compromise the overall function of leave areas (as was found for the Jones and Hardscrabble Units discussed above). This strategy could be broadly applied if a broad-scale inventory found that windthrow was affecting only a relatively minor area. The acceptance of occasional windthrow in some areas would be more justifiable if a sub-set of especially critical sites had been identified for a lower-risk treatment approach.

3. **Same as #2, but employ specialized edge treatments, such as feathering, or crown topping for exposed or critical areas.** This approach has the same primary advantage as #2, i.e. the use of natural topographic breaks. However, it is advantageous over #2 in cases where blowdown of edge trees could create resource impacts, perhaps by triggering a landslide or damaging downwind trees in the process of falling.

4. **Replace mature trees on unstable areas with a more windfirm and/or sprouting species.** This approach would involve removing mature trees from highly exposed terrain where a leave area of any configuration would be likely to blow down, and create stand conditions that would experience less windthrow through future timber rotations. The major drawback with this strategy would be the period of reduced rooting strength following removal of the present overstory. An obvious species for this strategy would be bigleaf maple, which has been found to be less prone to windthrow than conifers (Grizzel and Wolff, 1998), and is commonly observed to break, rather than uproot, under stress. Maple however is inferior to conifers in terms of rooting strength and hydrologic functions (interception of rain and snow). Once established, a sprouting hardwood species could allow partial harvest while retaining considerable rooting strength. Much could be learned by planting maple in areas where mature trees have already blown down, such as Hardscrabble Site A. This approach may be well suited for highly exposed hollows, which are poorly suited to exposed leave areas.

Given the diversity of terrain and resource vulnerabilities across the landscape, it may be useful to implement a combination of these approaches.

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Appendix 1. Calculations of changes in groundwater flux following windthrow at Jones Creek Unit

Acreage associated with deep-seated landslide and groundwater recharge area

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Active landslide:		18.0 acres
Groundwater Recharge Zone (GRZ) sub-areas:		
- cut with Jones FPA	2.4 acres	
- leave area – timber still standing	8.0 acres	
- leave area – portion wind-thrown	1.2 acres[1]	
Entire GRZ		11.6 acres
Total slide + GRZ		29.6 acres

1 - Estimated 70% of trees wind-throw within 1.7-acre area above the new road = 1.2 acres.

Relevant hydrologic conditions in vicinity of Jones Creek Unit (all in area-inches)

Annual Precipitation = 70"

Annual evapo-transpiration with mature forest[2] = 31"
Annual evapo-transpiration immediately after logging[2] = 12"

Net increase in evapo-transpiration for areas logged = 31"-12" = 19"
(immediately after logging, will decrease with time)

Annual groundwater input with forest = 70 - 31 = 39"
Annual groundwater input after logging or windthrow = 70 – 12 = 58"

2 - Average of three watershed studies at comparable sites in Oregon Cascades and Coast Range, Summarized in Miller and Sias 1997.

Area-averaged total groundwater inputs (area-inches) from combined landslide and GRZ

Prior to Jones Creek harvest (entire area forested) = 39"

Following Jones Creek harvest = (2.4 ac. * 58" + 27.2 ac. * 39")/29.6 ac. = 40.5"
This represents a 4% increase over pre-logging inputs

Following fall 1998 = (3.6 ac. * 58" + 26.0 ac. * 39")/29.6 ac. = 41.3"
This represents a 6% increase over pre-logging inputs, or a 2% increase over post-logging and pre-windthrow.

APPENDIX 11-5

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Occurrence of Windthrow in Forest Buffer Strips and its Effect on Small Streams in Northwest Washington

Abstract

Retaining streamside buffers has become a common way of protecting streams during timber harvest operations. Trees within forest buffers help stabilize streambanks, provide shade, and serve as a source of large woody debris. However, buffer trees are often subject to increased levels of windthrow which may impair some buffer functions. Forty (40) forest buffers bordering small, non-fish bearing streams in northwest Washington were assessed to quantify the level and in-stream effects of windthrow 1 to 3 years after clearcut harvest of adjacent timber. On average, windthrow affected 33 percent of buffer trees and ranged from 2 to 92 percent across the 40 sites. Sixty-seven percent of windthrown trees fell to the north, northeast, or northwest, while only three percent of the total fell towards the south. Large woody debris present in streams at the time of harvest was significantly larger than debris recruited as a result of buffer windthrow (t-test; $p<0.01$). Windthrow increased total in-stream large woody debris piece counts by 52 percent. Seventy-five percent of in-stream large woody debris pieces recruited to streams post-harvest were suspended above the bankfull channel while four percent stored sediment. Seventeen percent of uprooted trees delivered sediment to stream channels. The average volume input was 0.16 cubic meters per uprooted tree and 0.48 cubic meters per 100 meters of stream channel at 39 sites where mass wasting did not occur. At most sites, the volume of sediment input to streams was small relative to the amount stored behind obstructions. Large woody debris was the primary component of 93 percent of in-stream obstructions which stored sediment.

Introduction

Tree mortality resulting from windthrow (uprooting and stem breakage) has been a concern to forest land managers in the Pacific Northwest for most of this century. From a timber production perspective, windthrown trees represent an economic loss. These trees lose commercial value rapidly and salvage operations are often costly. Additionally, if not salvaged, insects attracted to the dead trees can spread into surrounding timber. From a broader ecological perspective, windthrow is a natural occurrence, and downed trees contribute to forest and stream productivity.

Since the 1970s, the establishment of forest buffers has increasingly become a way of protecting streams during timber harvest operations. A common rationale for retaining streamside buffers is the assumption that they can provide many of the same functions as an intact forest. However, trees within buffers are subject to increased wind exposure and significant amounts of windthrow can impair some buffer functions. The net effect of windthrow on streams is often debated from water quality, fish habitat, channel morphology and legal liability perspectives.

State and private forest land managers in northwest Washington have established buffers which exceed state Forest Practice rules on many small, non-fish bearing streams during the past several years. Instances of severe windthrow in these buffers have caused managers to question the practice of retaining "non-required" buffers. This study was undertaken to develop quantitative information regarding the fate and function of second-growth forest buffers retained along small, non-fish-bearing streams.

Published studies dating from the 1950s document a wide array of site, tree and forest stand characteristics that influence windthrow occurrence in Pacific Northwest forests. Regrettably, data are lacking to support the cause-and-effect relationships reported by many of those studies (Rollerson 1982). Early windthrow studies in Washington and Oregon focused on mortality along clearcut harvest boundaries and offered recommendations for cutting-line placement to reduce windthrow (Ruth and Yoder 1953; Gratkowski 1956; Steinbrenner and Gessel 1956). Research emphasis on windthrow shifted to streamside buffers in the 1970s as buffers became more common on public and private forest lands (Moore 1977; Hobbs and Halbach 1981; Steinblums et al. 1984; Andrus and Froehlich 1988; Sherwood 1993; Timber, Fish and Wildlife 1994; Mobbs and Jones 1995).

Streamside trees can exert significant influence on channel morphology and fluvial processes in small, low-order streams of the Pacific Northwest (Naiman et al. 1992). Standing trees and/or their root systems help retard streambank erosion and maintain stability of stream-adjacent hillslopes (Sullivan et al. 1987). Fallen trees and limbs supply in-stream woody debris which helps store sediment, dissipate streamflow energy, and create channel complexity. Despite these positive effects of woody debris on channel morphology, our understanding of the role of riparian and stream-adjacent forests in supplying wood has developed only recently (Bisson et al. 1987).

In this study, we characterized tree condition, large woody debris function, and stream sediment input and storage within forty (40) streamside buffers and associated non-fish bearing streams 1 to 3 years following clearcut harvest of adjacent second-growth timber. The objectives of this study were to:

1) quantify the amount and type of tree windthrow by species;

2) assess the abundance and function of in-stream large woody debris;

3) quantify the volume of in-stream sediment stored in discrete accumulations or wedges and the volume of sediment delivered to stream channels from uprooted trees.

Methods

Site Selection

State and private forest land managers were asked to identify potential study buffers adjacent to small streams on the lower, west slope of the North Cascades within the Stillaguamish, Skagit and Nooksack river basins of northwest Washington. From these potential sites, we randomly selected 40 buffers that met the following criteria:

1) non-fish bearing stream >1 meter average width;

2) buffer had a continuous, 180 meter or longer reach within the harvest unit;

3 clearcut harvest of adjacent timber occurred during the previous three years;

4) buffer trees were retained on both sides of the stream.

While the large majority of buffers had no removal of live trees, harvest of selected larger conifer trees did occur at three sites. The buffers were typical of merchantable, second-growth forest stands in northwest Washington, ranging in age from 40 to 60 years.

Inventory Procedure

Field work was completed during the summer of 1996. Data were collected within a 150 meter reach randomly located within each buffer. Total buffer length rarely exceeded 300 meters, thus the study reach usually included at least half of the total buffer length (≥50% sample).

Each study reach was divided into 15 meter segments. Channel gradient was measured for each segment; bankfull channel width, buffer width (slope distance), and adjacent hillslope gradients were measured at each segment node (11 locations). Buffer width and hillslope gradients were measured perpendicular to stream orientation. The "forming structure" associated with each in-stream sediment wedge was determined and stored sediment volume was estimated based on surface area and step height. Four classes of forming structures were identified: (1) pre-harvest large woody debris, (2) post-harvest large woody debris, (3) combination of pre- and post-harvest large woody debris, or (4) bedrock and/or boulder.

In-stream large woody debris >10 centimeters in diameter and >1.5 meters in length was tallied. Hydraulic function (sediment storage, bank protection, bank erosion, channel roughness, or bridging) and time-of-entry (pre- or post-harvest) was recorded for each piece lying within the vertical projection of the bankfull channel. Woody debris pieces outside this zone (i.e., on adjacent hillslopes) were not included in the inventory. Post-harvest debris pieces were differentiated from pre-harvest pieces based primarily on physical condition. It was assumed that pieces in more advanced stages of decay had been recruited to the channel prior to harvesting, while pieces with intact bark and/or foliage were of post-harvest origin (i.e., 1 to 3 years since time of recruitment). In addition, the degree of embeddedness exhibited by a particular piece was often used as an indicator of recruitment timing.

All standing, uprooted, and broken trees 15 centimeters diameter at breast height (DBH) and larger were inventoried. Downed trees that appeared to result from windthrow prior to timber harvest were not inventoried. Such trees were typically in a more advanced state of decay as evidenced by loose or missing bark, and loss of branches and/or foliage. Tree condition, (standing, uprooted, or broken), diameter at breast height (DBH), distance from channel and where applicable, direction of fall, was measured. The area downslope of each uprooted tree was examined for evidence of sediment delivery to the stream channel. Where sediment delivery occurred, the volume was estimated based on surface area and depth of exposed root mass and evidence of soil movement to the channel.

Results

Site Characteristics

Most study streams exhibited morphologies typical of step-pool or cascade channel types as described by Montgomery and Buffington (1993). Streams were generally small, averaging less than 3 meters in bankfull width (Table 1). Channel gradients varied considerably and averaged 24 percent (Table 1). The outer edges of buffers often corresponded with distinct topographic slope breaks. Total buffer widths (both sides of stream) averaged 26 meters, while hillslope gradients averaged 39 percent (Table 1). Sites with lower gradient channels and adjacent hillslopes were usually located in relatively wide valley bottoms while sites with steeper channels and adjacent hillslopes tended to be at higher elevations in midslope topographic positions.

The number of trees inventoried within buffer sites ranged from 60 to 537. Variations in the number of trees inventoried were attributable to differences in buffer width and stand density between sites. Stand densities prior to harvest averaged 507 trees/hectare or 47.4 m^2 basal area/hectare (Table 1). Conifer species comprised at least 75 percent of stand density (number of trees and basal area) at 19 of the 40 sites and 90 percent or more at 14 sites. Tree DBH averaged 32.9 centimeters (Table 1).

The most common species was western hemlock (*Tsuga heterophylla*), which accounted for 33 percent of all trees inventoried. Western redcedar (*Thuja plicata*), red alder (*Alnus rubra*), and Douglas-fir (*Pseudotsuga menziesii*) accounted for 22 percent, 20 percent, and 10 percent of all trees, respectively. Bigleaf maple (*Acer macrophyllum*), Pacific silver fir (*Abies amabilis*), Alaska yellow cedar (*Chamaecyparis nootkatensis*), and black cottonwood (*Populus trichocarpa*) comprised the remaining 15 percent of trees inventoried.

Windthrow

Windthrow averaged 33 percent of stand density across the 40 sites (Figure 1). This was true regardless of whether windthrow was calculated as a proportion of total stems (trees/ha) or as a proportion of total basal area (m^2/ha). Uprooting was the more common form of windthrow, averaging 27 percent of stand density while breakage accounted for the remaining six percent (Figure 1). One-third or less of the trees were windthrown at 24 sites while more than two-thirds of the trees were windthrown at three sites.

The level of windthrow varied among tree species. Pacific silver fir and western hemlock experienced the highest levels of windthrow at 37.3 and 36.0 percent of total stems, respectively. Bigleaf maple was least subject to windthrow, with 7.5 percent of trees being uprooted or broken. Windthrow occurred at intermediate levels for red

TABLE 1. Characteristics of 40 forest buffers and associated non-fish-bearing streams in northwest Washington: channel width (average channel width), buffer width (average buffer width on both sides of stream), channel gradient (average channel gradient), hillslope gradient (average hillslope gradient, both sides of stream), stand density (stand density, expressed as trees/hectare and m^2 basal area/ha; includes standing, uprooted, and broken trees), and stand diameter at breast height (average diameter, includes standing, uprooted and broken trees).

	Channel Width (m)	Buffer Width (m)	Channel Gradient (%)	Hillslope Gradient (%)	Density (trees/ha)	Stand Basal Area (m^2/ha)	DBH (cm)
Mean	2.7	26.3	24	39	484	47.4	32.9
Min	1.4	8.5	1	3	261	20.0	24.1
Max	5.7	64.9	63	75	995	87.3	50.0
S.D.	1.0	13.9	15	18	160	13.0	5.2

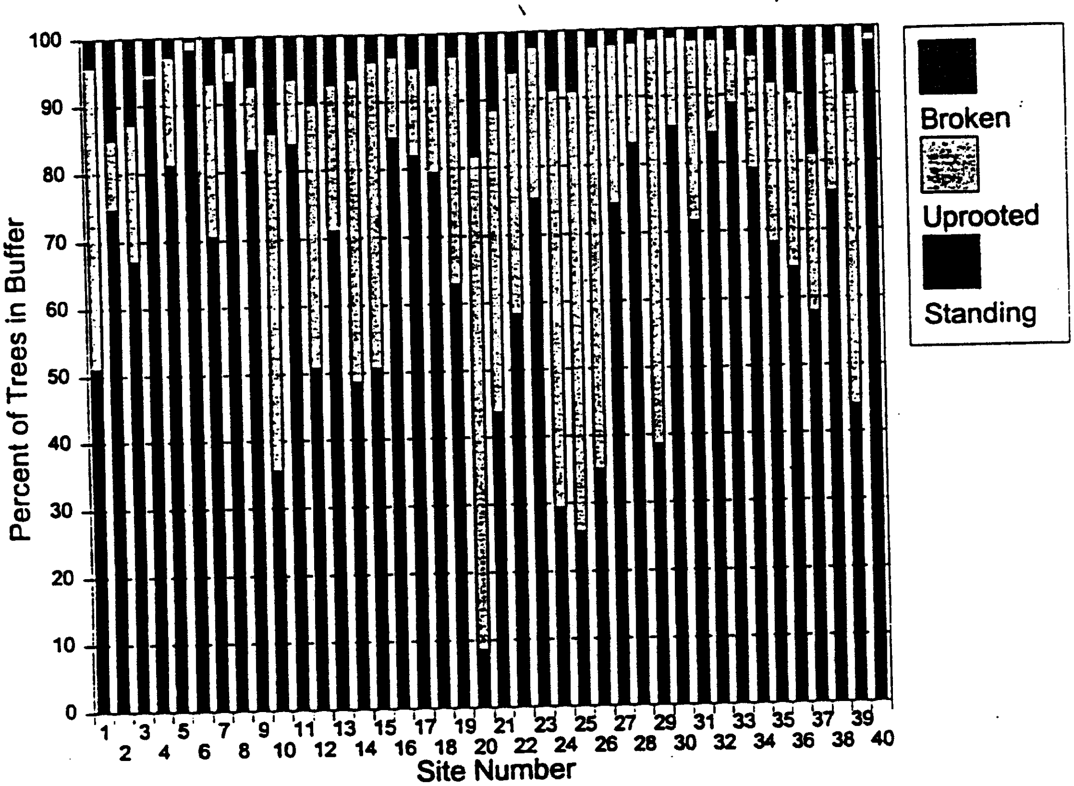

Figure 1. Proportion of standing, uprooted, and broken trees in 40 forest buffers in northwest Washington (each bar represents one site).

alder (17.2 percent), Douglas-fir (20.2 percent), and western redcedar (21.8 percent). Relatively high levels of windthrow for Pacific silver fir and western hemlock were documented in both mixed species stands as well as stands dominated by these species.

Average diameters of windthrown trees were significantly greater than standing trees for four of the six most common species ($p<0.01$, Table 2). Windthrown western redcedar, red alder, Douglas-fir, and Pacific silver fir tended to be larger than standing trees of the same species while no difference between windthrown and standing trees existed for western hemlock and bigleaf maple.

The direction of fall of windthrown trees was strongly influenced by prevailing southerly winds. While 67 percent of all windthrown trees fell to the north, northeast, or northwest, only three percent of the total fell towards the south (Figure 2). This pattern seems to be independent of stream/buffer orientation since the 40 sites were fairly evenly distributed with respect to the four cardinal directions (10 sites were oriented north-south, 8 were oriented northeast-southwest, 10 were oriented east-west, and 12 were oriented northwest-southeast).

In-Stream Large Woody Debris

Approximately one-third of all in-stream large woody debris pieces entered the stream following adjacent clearcut harvest. The proportion of post-harvest debris within the bankfull channel ranged from 2 to 77 percent of total pieces across the 40 sites. Post-harvest large woody debris comprised 25 percent of total woody debris pieces at 16 sites and 50 percent at seven sites. Piece frequencies averaged 0.66 pieces/meter (range = 0.05 to 1.34 pieces/meter) while debris volumes averaged 0.050 m^3/m^2 (range = 0.004 to 0.107 m^3/m^2).

In-stream large woody debris diameters averaged 28 centimeters (range = 21 to 37 centimeters). Pre-harvest debris was significantly larger than post-harvest debris when comparing mean

TABLE 2. Comparison of mean diameter at breast height (cm) and Standard Deviation (SD) of standing and windthrown trees and mean diameter (cm) of in-channel large woody debris deposited pre- and post-harvest in 40 forest buffers associated with non-fish-bearing streams in northwest Washington.

Species	Standing Trees Diam.	Standing Trees SD	Windthrown Trees Diam.	Windthrown Trees SD	P-value[1]
Bigleaf maple	32.5	(8.6)	32.3	(3.6)	0.450
Douglas-fir	38.9	(11.4)	42.2	(7.4)	<0.001
Red alder	33.0	(12.2)	34.8	(8.1)	<0.001
Western redcedar	29.2	(13.5)	30.7	(7.9)	0.003
Pacific silver fir	28.4	(4.6)	33.8	(4.6)	<0.001
Western hemlock	30.2	(13.7)	30.0	(11.2)	0.114
	Pre-harvest		Post-harvest		P-value[1]
Large woody debris	30.0	(20.8)	24.9	(13.7)	<0.001

[1]P-values for mean tree diameters were based on Mann-Whitney rank sum tests and P-values for large woody debris diameters were based on a Student's t-test.

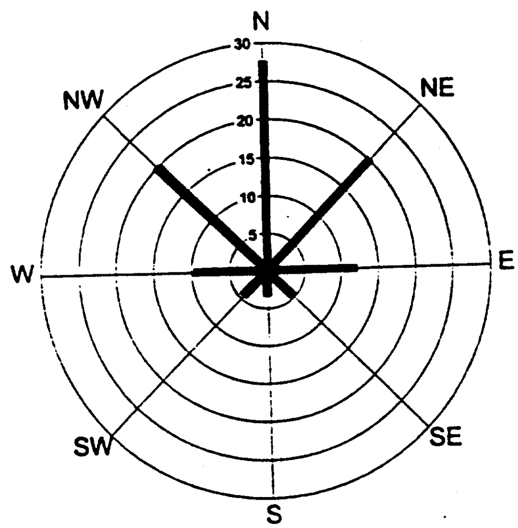

Figure 2. Percent of windthrown (uprooted and broken) trees falling in a given direction. Data is from 40 forest buffers in northwest Washington (n = 2,288).

piece diameters (p<0.01, Table 2). Pre-harvest debris averaged 30 centimeters in diameter while debris of post-harvest origin averaged 25 centimeters in diameter. Forty percent of pre-harvest debris pieces were larger than 30 centimeters in diameter while only 28 percent of post-harvest pieces fell into this category. Seven percent of pre-harvest debris and less than 2 percent of post-harvest debris was larger than 60 centimeters in diameter.

Approximately 66 percent of all large woody debris pieces were located within the bankfull streamflow zone; channel roughness was the primary function associated with 55 percent of these pieces while 32 percent stored sediment. Thirty-four percent of all woody debris pieces were suspended above the bankfull streamflow zone. While these pieces currently exert no direct influence on fluvial processes, they may become incorporated into the channel at a later date.

Figure 3 illustrates the function class distribution for both pre- and post-harvest large woody debris pieces. Eighty-five percent of pre-harvest debris pieces were located within the bankfull flow zone while 15 percent bridged the channel (Figure 3a). Twenty-eight percent of large woody debris pieces that entered streams post-harvest had a direct influence on channel processes (Figure 3b). Most post-harvest woody debris pieces bridged the stream channel (73 percent); post-harvest pieces accounted for 72 percent of all large woody debris pieces in this function class (984 of 1,364 pieces).

Sediment Storage

An average of 3.8 sediment wedges/100 meters of stream channel was recorded across the 40 sites. Seven sites had no wedge-associated storage within the study reach while 25 sites had between 0.5 and 25 m^3 of sediment stored in wedges (Figure 4). Average wedge volume was less than 3.0 m^3 for 28 of the 33 sites where wedges were present.

Large woody debris dams were the primary forming mechanism for 93 percent of all sediment wedges; the remainder were formed by bedrock or boulder obstructions. Debris dams comprised primarily of pre-harvest large woody debris formed 76 percent of inventoried wedges while post-harvest debris dams formed 5 percent of

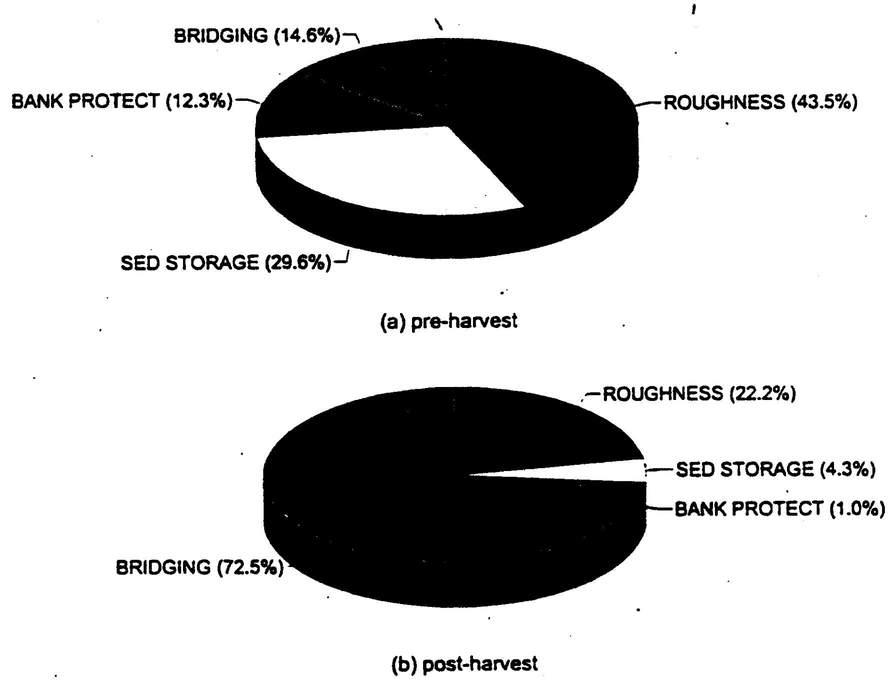

Figure 3. Function class distribution for in-stream (a) pre-harvest large woody debris (n = 2,611) and (b) post-harvest large woody debris (n = 1,357) associated with 40 non-fish bearing streams in northwest Washington.

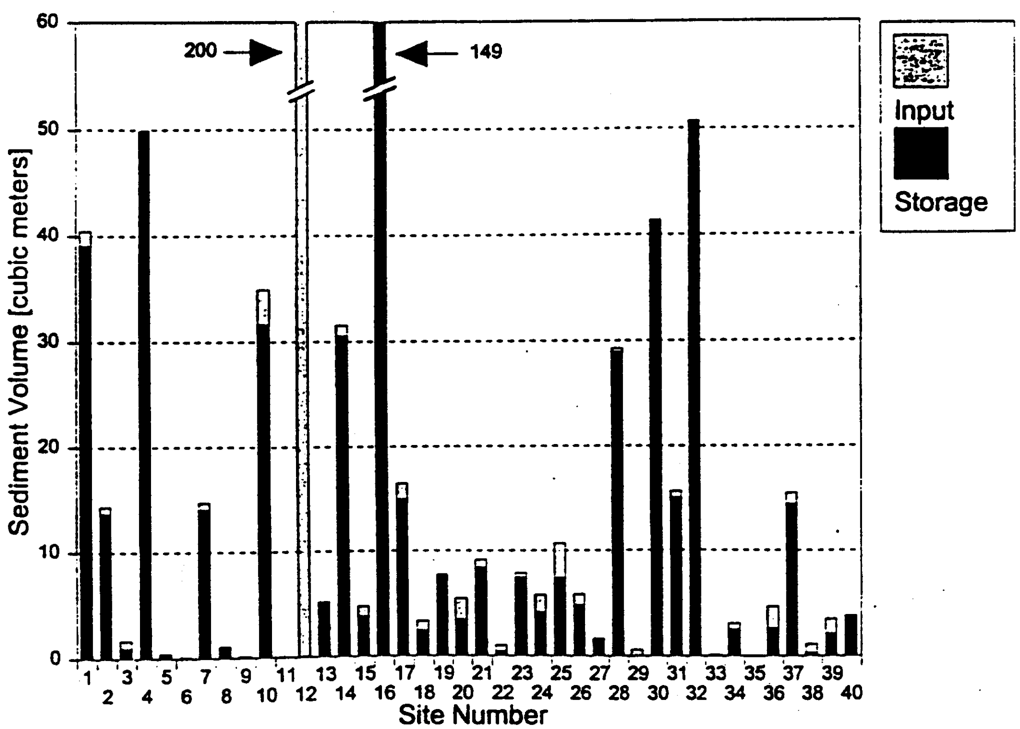

Figure 4. Sediment input and storage within 40 non-fish bearing streams in northwest Washington. Each bar represents one 150-meter stream reach. Sediment input is associated with uprooted buffer trees; sediment storage is associated with in-stream wedges created by obstructions or "dams".

wedges. Debris dams usually consisted of several pieces of woody debris anchored by larger key pieces of wood, boulders or bedrock. In many cases, the accumulated debris served to increase the height of the debris dam, thereby increasing its storage capacity. Debris smaller than our minimum piece size, and not included in the inventory, comprised a significant portion of some structures: debris dams composed wholly of such small debris also stored significant sediment volumes.

Sediment Delivery

Seventeen percent of uprooted trees delivered at least some sediment to stream channels. No sediment delivery occurred at three sites, <1 m^3 was delivered at 27 sites, between 1 and 2 m^3 was delivered at 8 sites, and >2 m^3 was delivered at two sites (Figure 4). A disproportionate amount of the total sediment volume delivered at all sites resulted from uprooting at a single site. A mass wasting event, probably triggered by uprooting of several large trees, delivered an estimated 200 m^3 of material to the channel (Figure 4). This site was characterized by steep channel-adjacent slopes comprised of deep, unconsolidated glacial outwash materials. This was the only site with this combination of geology and landform. Excluding sediment delivery at this site, inputs attributable to uprooted trees averaged 0.48 m^3 per 100 meters of stream channel.

Most windthrow-related sediment delivery to streams was associated with trees located within 3 meters of the channel edge. Eighty-five percent of the sediment delivered to stream channels at 39 of the 40 sites originated from within that zone (the mass wasting site was not included as its delivered volume exceeded the total of all other sites). Uprooted trees that fell toward or across the stream usually did not deliver sediment because the exposed portion of the rootwad faced away from the stream. Sediment inputs originating beyond 3 meters usually reached the channel as a result of trees sliding or rolling down a steep slope. However, in most cases, the rootwads of buffer trees did not move downslope after being uprooted.

At 23 of the 40 sites, sediment stored in wedges was approximately 10 times greater than the volume delivered to stream channels as a result of uprooting (Figure 4). Where delivery equaled or exceeded storage, channel gradients and/or valley confinement were generally not conducive to the formation of sediment wedges. High-gradient channels dominated by bedrock often had little capacity for sediment retention. Low gradient, unconfined channels contained large volumes of stored sediment, but most sediment was not stored in distinct wedges that met our inventory criteria. Sediment storage in these cases often occurred on adjacent floodplain landforms.

Discussion

Windthrow

In general, we found higher levels of windthrow than has been reported elsewhere in the Pacific Northwest (Table 3). Only one study, Steinblums (1978), reported average windthrow levels similar to those found by this study. The relatively high levels of windthrow found may result from

TABLE 3. Summary of reported buffer strip windthrow values in the Pacific Northwest.

Study	Location	# Sites	Buffer Age (years)	Windthrow[1] Range(%)	Mean(%)
This study	northwest WA	40	1-3	2-92[2]	33[2,3]
Mobbs and Jones (1995)	southwest WA	90	1	0-100[2]	5[2]
TFW (1994)	Washington	91	3-4	0-80[2]	10[2]
Sherwood (1993)	western OR	16	15-29	0-65[3,4]	12[3,4]
Andrus and Froehlich (1988)	western OR	30	1-6	0-72[3]	22[3]
Hobbs and Halbach (1981)	western WA	37	2-5	0-17[2]	5[2]
Steinblums (1978)	western OR	40	1-15	0-78[3]	29[3]

[1]In some cases, windthrow includes both uprooted and broken trees, while in others, only uprooted trees are included.

[2]expressed as a percent of stand stem density (trees/ha).

[3]expressed as a percent of stand basal area (m^2/ha).

[4]represents windthrow that occurred over the period 1977-1990: uses Steinblums (1978) reported post-windthrow volumes as a basis for estimated windthrow.

soil, topographic, and stand characteristics unique to the North Cascades region.

Relatively recent glaciation in the North Cascades (10,000 years before present) has shaped large-scale landforms and influenced soil characteristics in ways that may influence windthrow. The typically broad, glaciated valleys and hillslopes often offer little topographic protection from winds. Buffers on small streams are commonly associated with narrowly incised channels that drain broad, exposed hillslopes. Other regions of the Pacific Northwest with highly dissected drainages may be less susceptible to windthrow due to greater protection afforded by local topography. Furthermore, soils in the region are generally shallow (< 1 meter) and underlain by compacted glacial till or bedrock which restricts root penetration and anchoring. A perched water table typically persists throughout the wet season where drainage is impeded. Sites with shallow, wet soils are typically more subject to windthrow (Stathers et al., 1994).

The tree species composition of buffers may also influence windthrow occurrence. Pacific silver fir and western hemlock comprised over a third of all trees tallied at the 40 sites and were most susceptible to windthrow. Studies which reported relatively low levels of windthrow examined sites generally dominated by deciduous tree species such as red alder (Mobbs and Jones 1995; Timber, Fish and Wildlife 1994; Hobbs and Halbach 1981), which tend to be more windfirm than most species.

Site conditions documented in this study illustrate the influence of prevailing southerly winds on tree fall direction. Such information may suggest that buffer orientation could influence the degree of windthrow at a given site. That is, one might expect buffers oriented perpendicular to the direction of prevailing winds would experience higher levels of windthrow than those oriented parallel to prevailing wind direction. In this study, we documented a wide range of windthrow levels and tree fall directions. However, we found no evidence to indicate that buffer orientation influenced windthrow levels. It is likely that the level of windthrow occurrence at a given site is a complex interaction of a range of factors which vary in their degree of influence from site to site.

In-Channel Large Woody Debris

Buffer windthrow increased the number of in-channel large woody debris pieces by 34 percent across the 40 sites within one to three years after harvest. Such short-term increases in wood loading suggests that buffer windthrow is a significant mechanism by which debris is recruited to streams soon after harvest. Furthermore, tree fall patterns we documented suggest that woody debris recruitment from forest buffers is non-random, with trees tending to fall towards the north. For streams with east-west orientations, this suggests that much of the debris recruitment occurring within a few years post-harvest will originate from the south side of the stream.

Much post-harvest debris recruited to channels was suspended over the stream and will do little to influence channel processes in the near-term. These pieces must undergo a secondary recruitment phase where they break apart and enter the bankfull flow zone. The time between the initial windthrow and this secondary phase will vary depending on the species, size, and condition of wood pieces. Secondary recruitment of smaller hardwoods is likely to occur in a matter of a few years while larger conifers may remain suspended for decades.

The role of woody debris in retaining sediment in small headwater stream channels of the northwest has been documented previously (O'Connor and Harr 1994; Potts and Anderson 1990; Megahan 1982). Potts and Anderson (1990) found that organic matter accounted for over 60 percent of total sediment storage within eight reaches of first to third order channels in western Montana. Similarly, Megahan (1982) reported that organic material formed 76 percent of channel obstructions associated with sediment storage in seven small drainages in the Idaho batholith. Removal of this material via salvage logging or stream cleanout would likely destabilize the channel (Bilby 1984) and increase sediment export from the system (O'Connor and Harr 1994). Thus, buffers may provide a long-term source of large woody debris which helps create and maintain debris loads and reduce sediment yields. However, large woody debris recruited as a result of windthrow (post-harvest debris) was significantly smaller in diameter than debris recruited prior to buffer establishment (pre-harvest debris). A portion of the pre-harvest debris load consisted of larger pieces recruited from the original forest. Smaller debris generally has a shorter residence time and may be less effective at creating and maintaining sediment storage sites compared to larger pieces.

Sediment Delivery

In most cases, the volume of sediment delivered to stream channels as a result of post-harvest windthrow was relatively small. Sediment delivery at all sites averaged 1.43 m^3/uprooted tree. However, the average was only 0.16 m^3/uprooted tree at 39 of the 40 sites where mass wasting was not associated with uprooted trees. Except under the unusual physical conditions present at this single site, windthrow did not accelerate mass wasting. Andrus and Froehlich (1988) reported an average delivery of 0.87 m^3/uprooted tree for windthrow in the Oregon Coast Range. They concluded that the volume of sediment delivered to streams was usually small compared to overall watershed sediment yield and that uprooted trees did not accelerate mass wasting. Increases in sediment inputs attributable to windthrow may be offset by sediment storage sites created by recruited woody debris; however, we found that relatively few post-harvest debris pieces were currently storing sediment (Figure 3b).

Most windthrow-generated sediment delivery originated from trees rooted in the streambank. This zone generally extends outward 3 meters from the channel edge and accounted for approximately 85 percent of windthrow-generated sediment delivery. While harvest of trees in this zone might reduce sediment input to streams, other buffer functions such as rooting strength, woody debris recruitment, and shade would be reduced or eliminated.

Conclusions

The magnitude of windthrow in buffers bordering small, non-fish bearing streams in northwest Washington is highly variable. Even so, observed windthrow levels were generally higher than those reported in studies for other areas in the Pacific Northwest.

In a managed forest landscape, buffer windthrow is likely the most significant mechanism by which large woody debris is recruited to stream channels. Such debris is an important structural component in small headwater streams where it forms debris jams which trap and store sediment. However, for narrow, confined stream channels, windthrown trees are commonly suspended above the channel, providing little immediate influence on channel processes and sediment routing.

Generally, results of this study indicate windthrow is not a significant source of sediment delivery to stream channels. In addition, volumes of sediment delivered to streams as a result of windthrow were small relative to the amount stored within the channel. A notable exception occurred at a single site where uprooted trees accelerated mass wasting and delivered large volumes of sediment to the channel. This was the only site where the forest buffer developed in deep, unconsolidated glacial outwash materials.

Forest buffers are often established to maintain a range of ecosystem functions: windthrow may compromise some of these functions (e.g., shade, water quality, streambank stability) while at the same time enhancing others (e.g., large woody debris recruitment, sediment storage). The extent to which these functions are affected will depend on the magnitude and spatial and temporal occurrence of windthrow.

Acknowledgements

Doug Couvelier and Adrian Garcia worked under difficult terrain and weather conditions to collect field data for this project. The Washington Department of Natural Resources - Northwest Region provided most of the financial support. Additional funding was provided by the Washington Department of Ecology. Crown-Pacific Corporation, The Campbell Group, Trillium Corporation, and the Department of Natural Resources assisted in identifying potential study sites and provided access. In addition, C. Andrus, R. Beschta, R. Bilby, W. Megahan, K. Sullivan, J. Agee, R. Feller, and three anonymous reviewers provided useful comments and suggestions on earlier versions of the manuscript.

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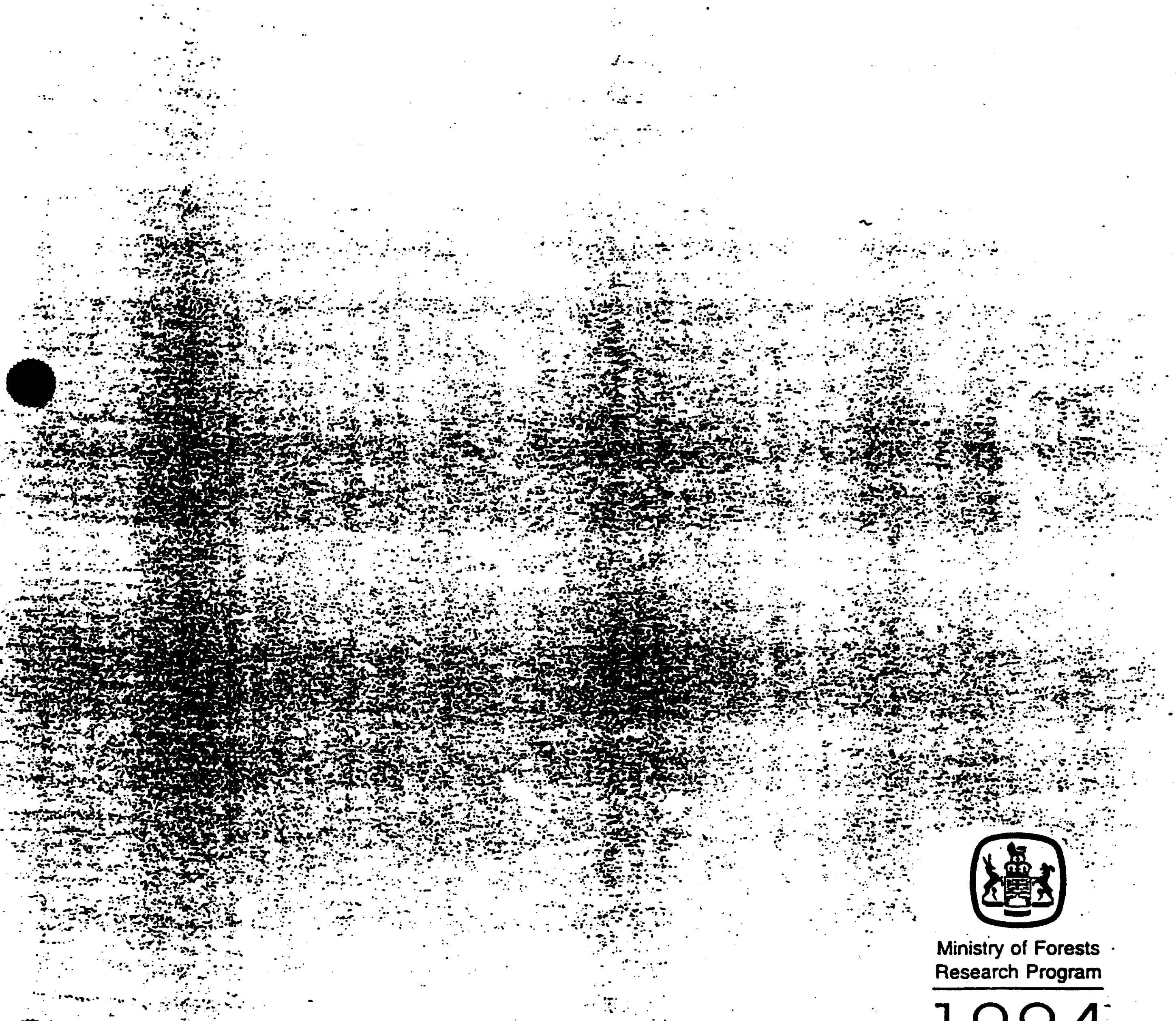
APPENDIX 11-6

Windthrow Handbook
for British Columbia Forests

Research Program Working Paper 9401



Ministry of Forests
Research Program

1994

Windthrow Handbook for British Columbia Forests

R.J. Stathers, T. P. Rollerson, and S.J. Mitchell

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This publication is Research Program Working Paper 9401

This Research Program Working Paper is an internal report of interim research results with field applications. It is intended to generate discussion and general feedback.

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PREFACE

Windthrow is dependent upon the interaction of a great number of factors. The importance of individual factors varies from place to place and from time to time. This handbook is intended to give users an introduction to the subject and to suggest possible options for assessing windthrow hazards and managing windthrow to minimize its impact. IT IS NOT A RULE BOOK. Users should interpret the material in this handbook in the light of their own local observations and with a good deal of common sense.

Sections 1 and 2 provide an introduction and background information about windthrow. Section 3 outlines the mechanics of windthrow. Section 4 describes the factors affecting windthrow. Section 5 outlines a method of evaluating windthrow hazard. Section 6 describes windthrow management strategies. A glossary and list of references is also included. Each section can be read independently. Users may want to skip the technical information describing the mechanics of windthrow.

To make the handbook as readable as possible, the authors have not included specific citations in the body of the text. References that apply to a specific section are noted at the end of each section. Complete citations are found in the References section. Some of the suggestions for management strategies are taken from research papers; others are based upon field observations and the authors' experiences in trying to manage windthrow.

The authors would appreciate user feedback on the usefulness and clarity of the material contained in this handbook. A questionnaire is located on a tearout page at the back of the handbook. Please take a moment to fill out the questionnaire and mail it to the address provided. User comments will enable us to expand and improve future editions of the handbook.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

Windthrow is a natural phenomenon affecting forests throughout British Columbia. Every year hundreds of hectares of trees are blown over in uncut stands and along cutblock boundaries and road allowances. At recurrence intervals of 10 to 20 years, thousands of hectares of forest are windthrown by gale or hurricane force winds. This damage results in considerable loss of revenue and disrupts long-term management plans. Windthrown timber that is not salvaged can also create a fire hazard and can produce habitat conditions that increase the risk of insect epidemics. For example. the spruce bark beetle (Dendroctonus rufipennis) can very rapidly spread from windthrown trees into adjacent stands where it can cause extensive damage.

As integrated management plans for forests become more complex and diverse. the potential effects of wind damage need to be considered more carefully. The feasibility of some treatments may be questionable on certain sites because of a high windthrow hazard. Smaller opening sizes, wildlife corridors, and streamside management zones are often prone to wind damage and require careful layout and edge stabilization treatments in high hazard areas.

The Forestry Commission in the United Kingdom has developed a quantitative windthrow hazard classification scheme for identifying where wind damage is most likely to occur. however, not enough is currently known about wind zones in B.C. forests to implement a similar system. A more qualitative approach toward a windthrow hazard classification system is all that is currently possible, given that very little windspeed data has been collected in our forests and that very little is known about the threshold forces required to overturn the wide range of species and crown classes that comprise stands in B.C. Even so, a classification scheme to stratify degrees of risk of wind damage that is based upon observations, experience, and the physical principles governing the windthrow process should serve as a good starting point to develop management strategies to reduce the risk of windthrow.

2 BACKGROUND INFORMATION

From a management perspective it is useful to categorize two types of windthrow. *Catastrophic* windthrow occurs infrequently when exceptionally strong winds cause widespread and extensive damage to large areas. Trees are usually blown over in a single direction (within about 30° of the storm wind direction) and stem breakage is common, particularly on deep, well-drained soils where good root anchorage occurs. *Endemic* windthrow occurs more regularly, but on a smaller scale. It usually occurs in areas that can be recognized as having an inherently higher hazard. It occurs as a result of numerous, lower-velocity windstorms and affects individual stems or small groups of trees. Endemic windthrow often spreads progressively from an abrupt or unstable boundary and is often an indirect result of forest management practices.

It is difficult to manage for catastrophic windthrow because of the nature of storm winds, but much can be done to reduce the areal extent and damaging effects of endemic windthrow.

Different types of wind damage have been recognized. These include: 1) stem break, where the bole of the tree snaps well above the ground, 2) stock break, where the bole snaps at ground level, 3) root break, (a rotational fall) where the tree is uprooted by pivoting on broken roots directly beneath the bole; and 4) tree throw, (a hinge fall) where the tree is uprooted by pivoting on the outer edge of a massive plate comprised of soil and roots. Similar forces are required to break or uproot trees and often both types of damage occur within a stand during a storm.

Stem break has been noted to occur more frequently during strong gales and hurricane force winds, particularly on sites where good root anchorage occurs (i.e. where the anchorage strength exceeds the turning force and the bole strength), and in trees that have been structurally weakened by disease. Trees with large height-to-diameter ratios, large crowns, and high crowns also tend to snap off rather than overturn.

Rotational falls usually occur after the main supporting bracket roots are progressively broken during a storm. They typically occur in trees with relatively small root systems, trees with root rot, or trees growing in sandy or wet soils that have low shear strength. Hinge falls occur more commonly in trees with a shallow, plate-like root system on very wet sites, or on shallow soils.

Windfirmness is the ability of a tree to resist overturning. It is a function of the balance between the anchorage or strength of the root/soil mass and the wind drag and gravitational forces applied on the tree crown. Other terms relevant to windthrow are defined in the glossary.

Suggested Reading

Catastrophic versus endemic windthrow: Alexander (1964, 1986), Somerville (1980), Holmes (1985), Busby (1965), Cremer et al. (1982)

Effects of disease: Hubert (1918)

Types of wind damage: Mayer (1987), Shaetzl et al. (1989), Cremer et al. (1982)

Windthrow hazard classification: Miller (1985)

3 MECHANICS OF WINDTHROW

Though it might initially appear that the process by which wind blows a tree over is very simple, a wide range of forces can actually cause windthrow. The mechanics of the process are complex and dynamic, and many interacting factors can be involved. It is useful to examine the mechanics of the windthrow process for a single tree to understand the role of various factors.

Windthrow occurs when the horizontal forces on a tree are transmitted down the trunk to create a torque that exceeds the resistance to turning of the root/soil system. The torque, or turning moment, at the base of the tree can be estimated by dividing the tree into height increments and summing the contribution of the torque from each height interval as follows:

$$\text{Torque} = \Sigma(F_i\, h_i) \qquad (1)$$

where h_i is the height of the i-th increment and F_i is the horizontal force on that increment. As trees grow taller they can become increasingly prone to windthrow. For example, a force of 100 N applied at a height of 10 m creates a torque of 1000 Nm, but the same force at the 30 m height generates three times as much torque.

Two horizontal forces contribute to the torque at each height increment. The first force is a function of the effect of wind on the crown at height i as follows:

$$F_i = \rho\, A_i\, C_{Di}\, u_i^2 \;/\; 2 \qquad (2)$$

where ρ is the density of air, A_i is the projected area of the crown perpendicular to the direction of the wind, C_{Di} is the drag coefficient of the crown, and u_i is the wind speed at height i above the ground. The second force is a gravitational force that is contributed as the tree sways away from the vertical axis as follows:

$$F_i = m_i\, x_i\, g \qquad (3)$$

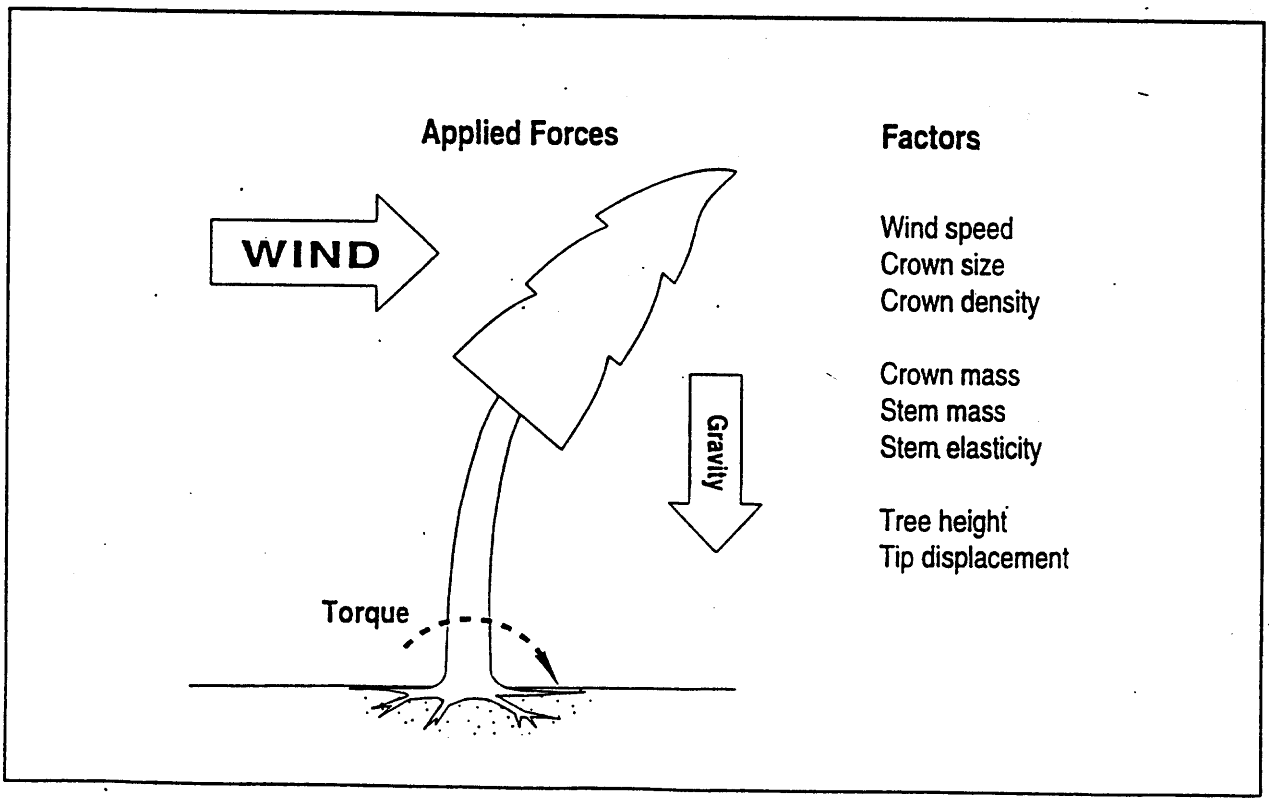

FIGURE 1. Factors affecting wind and gravitational forces acting on a tree.

where m_i is the mass of the height increment, x_i is the horizontal displacement from the vertical, and g is gravitational acceleration. The gravitational force is relatively weak compared with the force of the wind on the crown until the tree starts to sway well away from the vertical axis. At a sway angle of 15-20°, the gravitational force can become a considerable proportion of the total horizontal force.

The drag force on the crown is proportional to the area of branches and stems exposed to the wind, the drag coefficient of the foliage (i.e. how efficiently it intercepts wind), and the square of the wind speed (i.e. when the wind speed doubles, the drag force on the crown increases by a factor of four). Wind tunnel studies with whole trees have shown that the drag force is nearly proportional to the projected area of the canopy, drag coefficient, and wind speed. However, as wind speed increases, the canopy tends to bend and deflect and become more streamlined.

Drag coefficients have been found to vary considerably between species. Engelmann spruce and subalpine fir have stiff branches and needles and relatively high drag coefficients (~0.5-0.8) compared to the more flexible branches of lodgepole pine and Douglas-fir (0.3-0.6), or the very spindly branches and crowns of western hemlock (0.2-0.3). [Drag coefficients at wind speeds of 25 m/s and 10 m/s, respectively.] Taller individual trees growing within forest canopies that have uneven height or density distributions intercept more wind and therefore require stronger root anchorage to counter the increased drag force. The drag force of the wind on the crown results in branch and needle deflection. This force is transmitted to the stem, causing it to bend and sway. The sway period and amplitude are functions of the height, stiffness, and shape of the stem, the stiffness of the anchorage of the root system, the effect of adjacent tree crowns on motion damping and turbulence, and the speed and turbulence characteristics (gustiness) of the wind within and over the canopy. The presence of trees of varying heights and gaps or openings within a canopy act to increase atmospheric turbulence; however, relatively little is known about the effect of opening size or canopy architecture on the downstream wind field.

Studies of the relationship between the sway period and amplitude, damping, and structure of the wind turbulence have found that large eddies can contribute significantly to the shear stress on individual

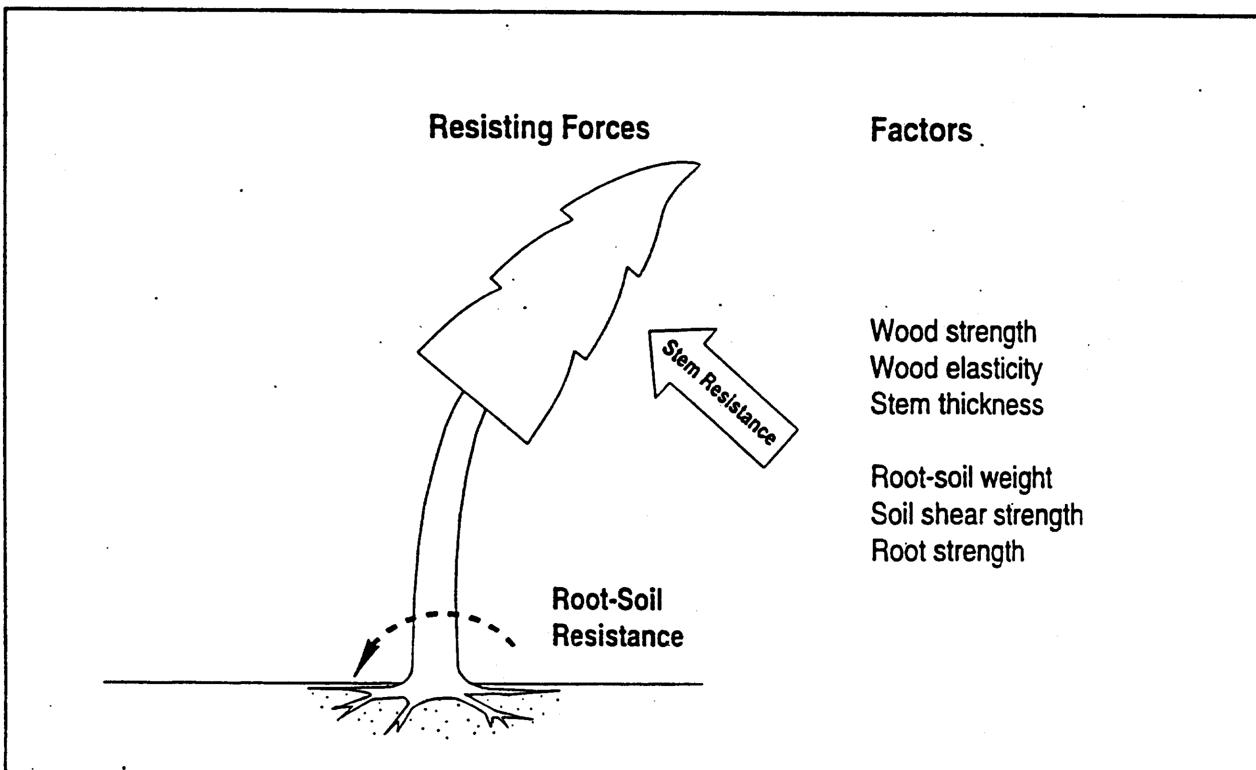

FIGURE 2. Factors affecting the resistance to wind and gravitational forces acting on a tree.

trees. When wind acceleration resulting from turbulence is in phase with the natural sway frequency of a tree, the amplitude of the sway can be increased considerably. Hence, even during relatively low wind speeds, a certain frequency of gusts (or eddy sizes) can transfer energy to a swaying crown that causes it to increase in amplitude over a period of a few sways until it reaches a threshold turning moment. The sway period of trees varies from about 3-6 seconds. Tall, slender, cylindrical stems sway more than short, conical stems. Damping of the swaying motion by contact with adjacent crowns can provide considerable force dissipation by spreading the force over many stems. Dense, even-aged lodgepole pine stands are often prone to windthrow and stem break after partial cutting because of their bole characteristics and the loss of damping through contact with adjacent crowns.

The drag force on a tree crown is counteracted by a number of resistances. As the wind speed increases, the main stem, branches, and needles are deflected by the wind such that the tree becomes more streamlined. As a result, the projected area of the canopy decreases and the drag coefficient decreases. Swaying of the bole also dissipates energy. The amount of deflection of the bole is dependent on its diameter, elasticity, and shape. A conical trunk is considerably stronger than a cylindrical trunk (in which strength is a function of the cube of the bole diameter/height). Older trees and open-grown trees usually have more taper than trees in even-aged, uniform canopies.

Relatively little is known about the threshold turning moments for the range of crown classes, heights, and stand densities for different species. The static turning moments of 10 m tall Sitka spruce trees were found to range from 3-14 kN m[*], and were well correlated with height and diameter. Threshold static turning moments

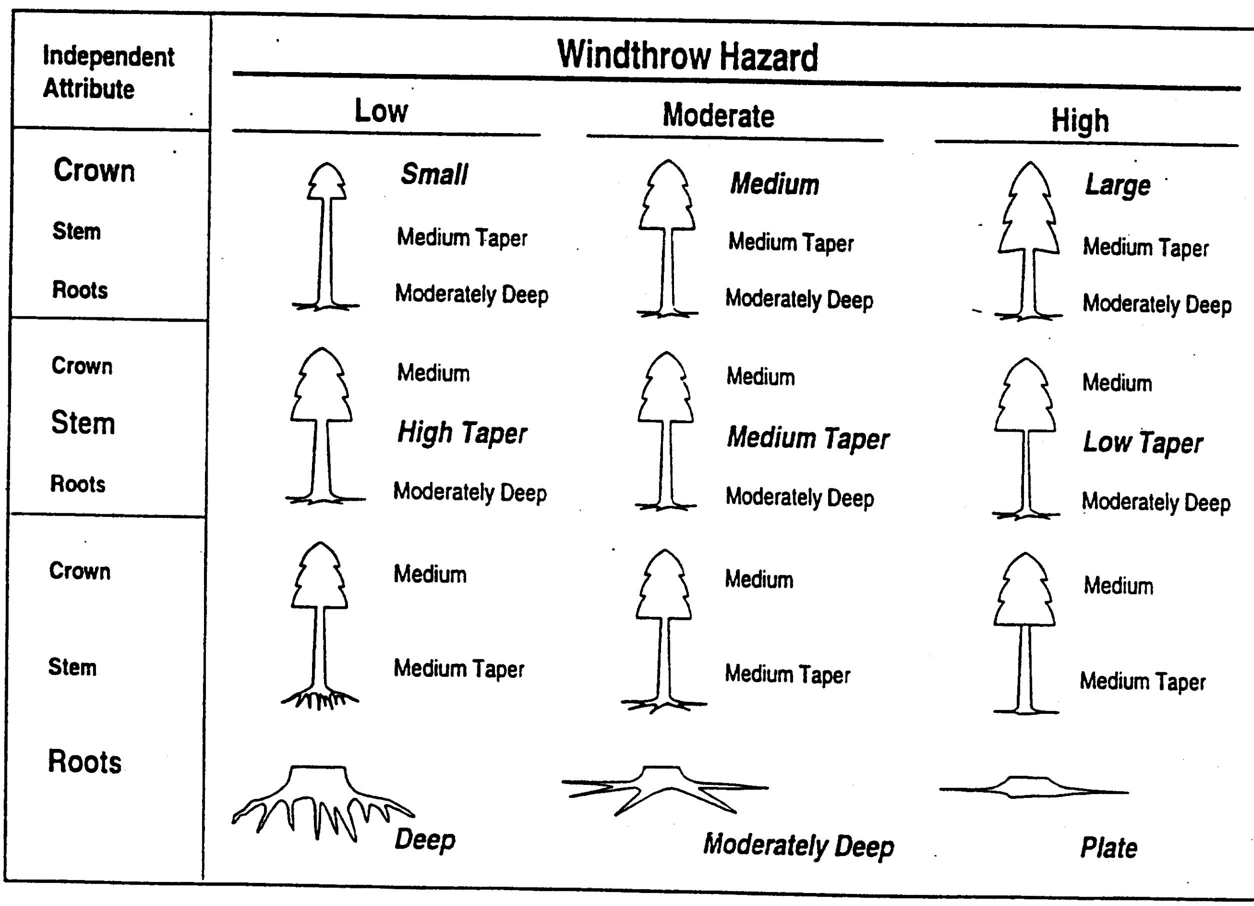

FIGURE 3. Crown, stem, and root attributes that affect the risk of windthrow.

[*] Units of torque are in kN m: kilo Newton metres. A force of 1 Newton metre is generated by applying a mass of 1 kg at a distance of 1 metre on a cantilever.

of 18-21 m tall Sitka spruce varied from to 9-33 kN m. Threshold turning moments in black spruce have been found to be well correlated with height and stocking density. with values ranging from about 5 kN m in 15 m tall stands to 14-18 kN m in 22 m tall stands. The turning moments required for uprooting and stem breaking have been found to be of similar magnitude. Turning moments are likely to be quite variable in old-growth stands because of the variability in species, canopy characteristics. ages, heights, densities, and rooting habits.

The characteristics of root systems, the factors affecting anchoring strength, and the dynamics of root shearing as a result of static and dynamic wind action on the canopy have been examined by several researchers. Most of this work pertains to Sitka spruce and Douglas-fir; however. it also applies generally to other species. These studies have shown that the physical properties of the soil that govern root morphology and the overall size of root/soil mass are the most important determinants of the strength of anchorage. Small increases in rooting depth and area can significantly increase the resistance to overturning.

During a storm, tree crowns sway back and forth with elliptical motion, the major axis of swaying in the direction of the wind. This motion continually applies tensile, compressive, and shearing stresses to all sides of the root system. Tree roots are about three times stronger under tension parallel to the grain than they are under compression in the same direction. Hence, the first root shearing usually occurs in small diameter roots on the leeward side of the tree as a result of compressive forces from forward sways. The loss of strength on the leeward side then allows a greater backsway and causes roots on the windward side to fail under compressive stress. On plate-like root systems, the resistance to pulling of the large lateral roots on the windward side of the tree contributes the most anchorage strength.

The pumping action of the root plates of large swaying trees is likely to cause progressive weakening of the soil-root system. Continual swaying during a storm progressively shears and weakens roots or abrades them if they are adjacent to rocks. When examining windthrown trees, it is often possible to see

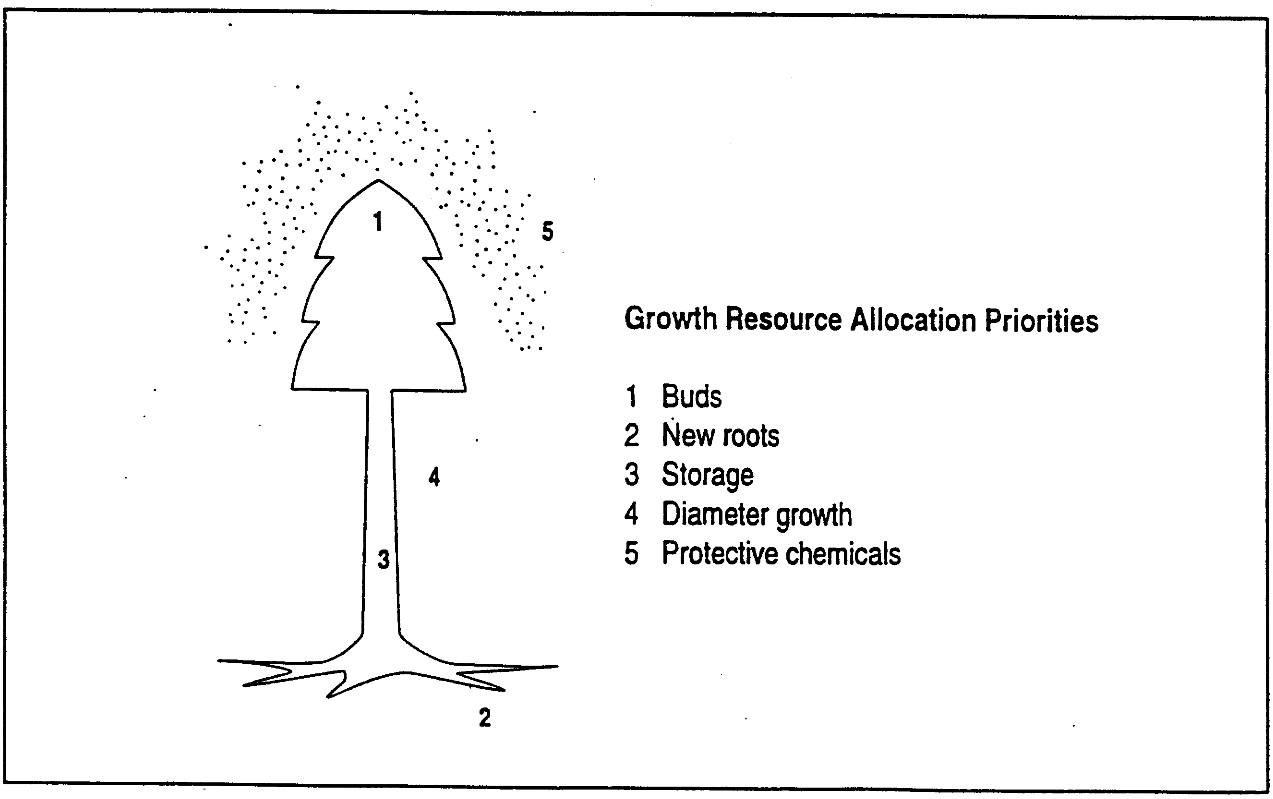

FIGURE 4. The normal hierarchy of growth resource allocation where production of foliage and fine roots takes precedence over stem and root diameter increment. (Source: After Waring and Schlesinger, 1985.)

where roots have been broken and abraded in previous storms and have subsequently callused over and healed. Longer duration storms of lower intensity or more frequent low intensity storms can sometimes cause windthrow by progressively weakening the soil/root system, especially if the soil is wet.

Major lateral roots (>0.5 cm diameter) largely determine the resistance to overturning. The stiffness of a root is proportional to the fourth power of its diameter; hence when a root forks into two equal branches, its stiffness is halved. Therefore, root systems comprised of large roots are stronger and provide more resistance to swaying than those with a great number of smaller roots. The force required to extract roots increases as a function of their diameter and length. Increased anchorage strength also results from the intermingling of root systems with adjacent trees. Stability may be quite sensitive to rooting symmetry, especially when rooting is restricted.

Windfirmness changes slowly as trees grow in response to their environment. To remain windfirm as they grow taller, stems and structural roots must be thickened in proportion to the additional wind and gravitational forces that must be withstood. In the normal hierarchy of growth (outlined in Figure 4), production of foliage and fine roots takes precedence over thickening of the stem and structural roots. Trees that grow in dense stands have relatively low individual windfirmness because the production of crown and fine roots uses most of the available growth resources. In contrast, trees that grow at a wide spacing are more windfirm because they develop larger root systems and thicker, tapered stems. The stimulus for additional thickening of structural tissues is wind-induced swaying. Specialized reaction wood may also be formed if stems are tilted or bent.

Windthrow management involves the use of treatments which modify root anchorage strength and wind force on the canopy.

Suggested Reading

Mechanics of windthrow: Petty and Swain (1985), Blackburn et al. (1988), Cremer et al. (1982), Mayer (1987), Oliver and Mayhead (1973), Fraser (1964)

Tree and stand effects: Fraser (1964), Mayhead (1973), Mayer (1987), Mayer (1989), Holbo et al. (1980), Coutts (1986), Smith et al. (1987)

Root system effects: Fraser (1962), Fraser and Gardiner (1967), Coutts (1983), Mergen (1954), Anderson et al. (1989), Day (1950)

Wind and tree growth: Jacobs (1954), Larson (1965), Mattheck (1991), Robertson (1987)

4 FACTORS AFFECTING WINDTHROW

The factors that affect windthrow are those that influence the effectiveness of root anchorage, the strength and aerodynamic properties of the tree, and the direction and characteristics of the wind within and above the stand. For simplicity these can be separated into individual tree characteristics, stand characteristics, root zone soil characteristics, topographic exposure characteristics, and meteorological conditions.

4.1 Individual Tree Characteristics

Ability to shed branches,

At the *individual tree level*, the following characteristics affect tree stability:

- the height, diameter, and shape of the bole
- the crown class and size of crown
- the strength and elasticity of the bole, branches, and needles
- the rooting depth and area, size and number of roots, and whether or not adjacent tree root systems interlock.

Members of a stand can have widely differing susceptibilities to windthrow because of variations in these characteristics.

Research results linking species to windthrow have been somewhat contradictory because of the interacting effects of site and stand characteristics on tree form. Many of these characteristics vary between species and so certain species may appear more windfirm than others. For example, on wet sites Western redcedar is considered to be more windfirm than hemlock and balsam fir because of its crown characteristics and rooting habits. Ponderosa pine is usually very windfirm because of its open-grown nature; however, Douglas-fir is also very windfirm on dry sites. On high-elevation sites lodgepole pine and Engelmann spruce often appear more windfirm than subalpine fir; however, their windfirmness may be more a function of site-specific conditions, age, or disease. Sound snags of any species that lack a crown to act as a sail are typically less vulnerable to windthrow than live trees. Species alone should not be considered a very reliable predictor of windthrow susceptibility.

Trees with large or medium dense crowns are more vulnerable to windthrow than trees with smaller, open crowns. Crown modification techniques such as pruning and topping to reduce the effective crown size and density can considerably reduce the risk of windthrow. Taller trees are also generally more prone to windthrow because of their greater potential turning moment. However, tall trees can be quite windfirm if they have been exposed to wind and are well rooted in deep, freely draining soil.

Many studies have indicated that the incidence of windthrow is increased in trees that have poor root anchorage resulting from saturated soils, soils with restricted rooting depths, or where root morphology is affected by treatments such as trenching or mounding.

Root and bole rots have been found to be associated with high frequencies of both windthrow and stembreak, because of their effects on root anchorage and bole strength. Surveys of windthrow in high-elevation Engelmann spruce-subalpine fir forests in the U.S. Rocky Mountains have found root or bole rots associated with about one-third of the wind damage. Other studies have shown that 20-50% of wind-damaged trees have evidence of infection by various types of rot.

Stem taper may be an important factor affecting susceptibility to stem breakage. The height-to-diameter ratio of dominant trees in even-aged stands has been found to be a good indicator of risk of stem breakage. Stem breakage is less likely in stands where trees have height-to-diameter ratios of less than 60. When the height-to-diameter ratio of a tree exceeds 100, it is more prone to windthrow and stem breakage.

*Crown class alone is not a reliable predictor of windthrow hazard. There is some evidence to suggest that dominant, codominant, and veteran trees are less susceptible to windthrow than the intermediate and suppressed crown classes if they have been exposed to wind for a long time. Older trees often have a higher windthrow hazard because they are typically taller, have greater stem-to-root ratios, and are more likely to have root diseases.

4.2 Stand Level Characteristics

At the *stand level*, individual trees can be made more or less prone to windthrow through the effects of:

- stand height and density
- species composition
- silvicultural treatments (thinning, pruning, edge feathering, ripping, draining, etc.).

Stand height and density affect wind flow and hence the drag force on individual trees. Dense stands are usually quite windfirm because of interlocking root systems, inter-tree crown damping during swaying, and the effect of the dense crowns on reducing wind penetration into the stand. The individual trees that make up a dense stand are often not windfirm in isolation because of restricted rooting as a result of competition and a high height-to-diameter ratio. These stands can be very prone to windthrow after thinning. Studies of model forests in wind tunnels have indicated that the drag force per tree can increase by up to 40% when the tree spacing increases from 25% of tree height to 40% of tree height

Younger stands are typically more windfirm than older stands. Old-growth stands can have a high incidence of root and butt rots which can make them more susceptible to wind damage. Older dominant trees and veteran trees can be very windfirm, particularly if they are deeply rooted and have been exposed to wind for a long time. Because of their greater exposure to wind, individual trees in thrifty, uneven-storied stands also tend to be more windfirm than canopies with a more uniform height. Some European research suggests that mixed deciduous and conifer stands may also be more windfirm.

Wind damage usually occurs in the first few years after harvesting, particularly where more susceptible trees are exposed to stronger winds as a result of harvesting. Trees can become more windfirm after a few years of exposure as they develop reaction wood in response to swaying. This response may take longer in high-elevation stands because of the slow growth rates resulting from the short growing season and harsh environmental conditions.

Certain operational treatments can increase the windthrow hazard by increasing the wind speed and turbulence. Clearcuts can create problems in this respect. Windthrow usually occurs on the downwind edge of cutblocks and can extend into the stand for hundreds of meters, although most damage is usually concentrated within the first 10-20 m of the cutting boundary. Less wind damage usually occurs on upwind boundaries and along boundaries parallel to storm wind directions. Opening size does not seem to have a significant effect on the amount of windthrow. However, as opening size increases there may be more opportunity to find windfirm boundary locations. In some areas, very small openings (<1 ha) have proven to be relatively windfirm.

Wind tunnel experiments with model forests have shown that the force on the downwind edge of a clearcut is dissipated within a short distance into the stand, but that turbulence resulting from accelerated wind flow over the edge of the stand causes zones of very high turbulence a few tree heights downwind until the flow is reattached to the canopy. This turbulence increases the risk of windthrow in this zone.

Thinning can significantly increase wind damage, particularly in dense, even-aged stands. Except for sites where root growth is restricted, plantations raised at lower stocking densities generally experience much less wind damage. Extensive damage can occur in stands that are heavily thinned, especially if dominants are removed and if the residual trees are tall and slender. A number of studies have shown that less wind damage occurs after low intensity thinnings (<25% of stand volume), while severe damage can occur in stands where the dominant trees have been removed.

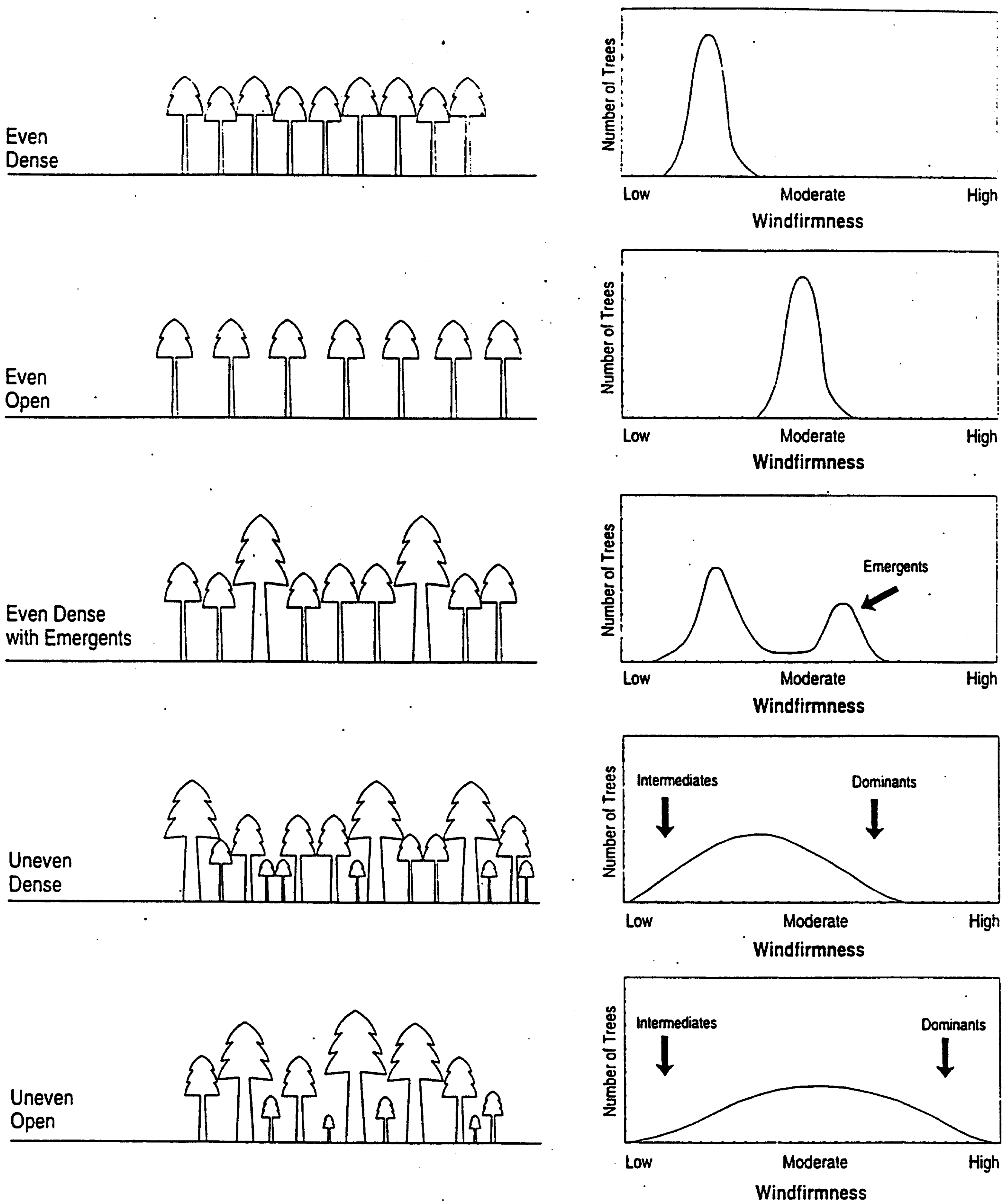

FIGURE 5. A comparison of distributions of the relative windfirmness of individual trees comprising stands with different structural characteristics.

Pruning in young stands should reduce windthrow by reducing the crown area exposure and hence the turning moment on the stem. However, some studies have shown mixed results, possibly because opening the canopy also increases the wind speed and turbulence within the canopy.

4.3 Soil Characteristics

Soil characteristics affect windthrow through the interaction of:

- depth
- drainage
- structure, density, texture, and stoniness on the anchorage strength of the root system.

Trees growing in deep, well-drained soils produce much larger root systems than those in soils where saturated conditions, high bulk density, stoniness, pans, or near-surface bedrock restrict root development. Typically, trees growing on deep, well-drained soils are much more windfirm than those growing on shallow or poorly drained soils. Trees growing in conditions where rooting is confined to the organic layer are often quite vulnerable to windthrow.

On shallow or very wet soils roots usually form a plate-like structure up to 4 m in diameter and often less than 0.4 m deep. This plate forms a foundation for the tree that provides adequate stability when the tree crown is protected from high winds within a canopy, but often does not provide enough anchorage strength if the adjacent canopy is removed.

Soils, particularly when wet, have shear strengths that are two to three orders of magnitude less than roots; hence adhesion and cohesion of the soil to individual roots plays a relatively small role in supporting the tree. Soil conditions appear to play a greater role in anchorage strength by affecting the total volume of the root system and the size of individual support roots.

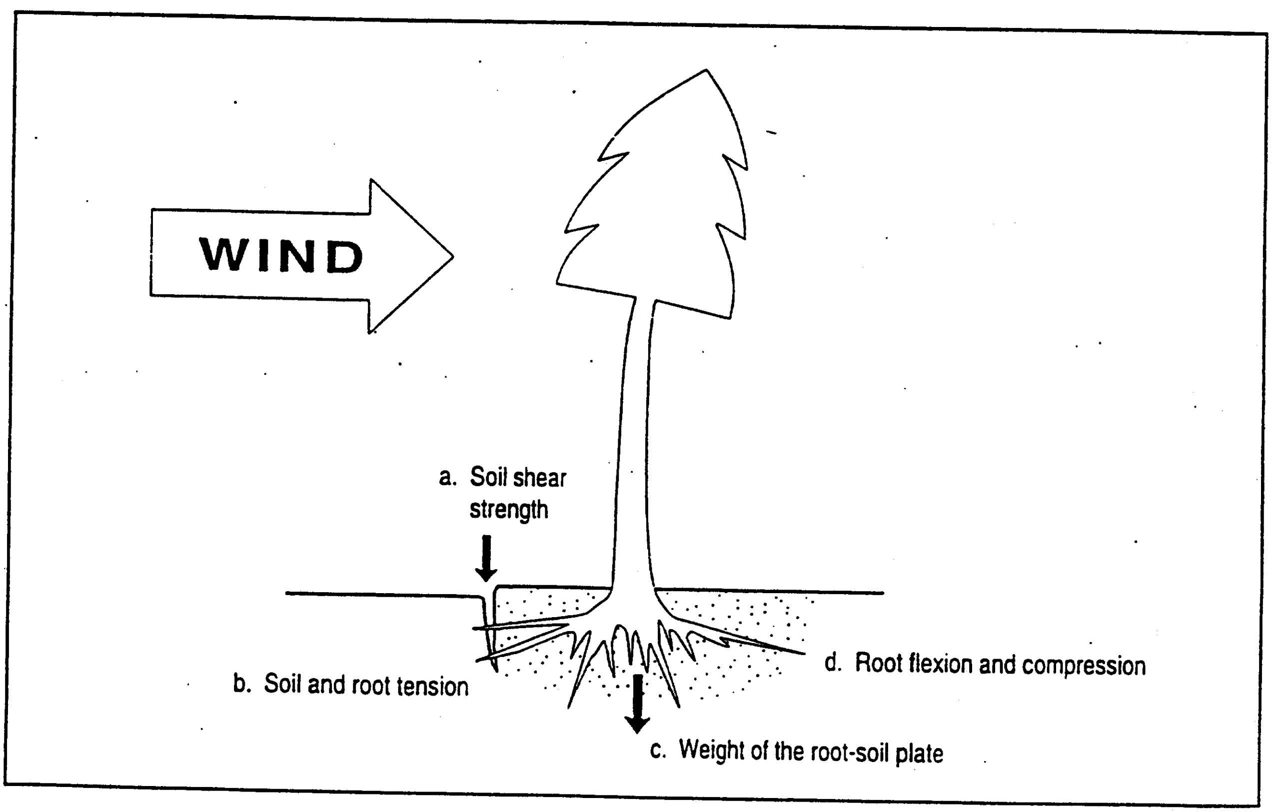

FIGURE 6. Root and soil factors affecting resistance to overturning. (Source: After Ruel, 1992.)

There appears to be a consensus in most windthrow studies that the *soil factors that control rooting depth contribute most significantly to the risk of windthrow.* Shallow rooting is most likely to occur on shallow soils overlying bedrock (e.g. Follisols) and on poorly drained sites where root growth is restricted by a high or fluctuating water table. Deeper rooting, and hence greater resistance to overturning, is more likely to occur on deep, well-drained Podzols and Brunisols than on organic soils or Gleysols. Luvisolic soils often have very dense (>1.6 Mg/m3), clay-rich horizons that can restrict rooting depths.

4.4 Topographic Characteristics

Topographic characteristics affect windthrow by modifying:

- wind exposure
- wind direction, speed and turbulence.

The effects of terrain on wind flow are complex, however, it is possible to characterize certain landforms where the inherent risk of windthrow is higher because of wind acceleration or increased turbulence. The speed and direction of the wind at a height of about 1000 m above the surface is largely governed by the atmospheric pressure gradient and rotation of the earth. Nearer the surface, this flow becomes increasingly turbulent as the frictional drag of surface features plays a greater role. Surface winds flow over and around hills and can change direction by up to 90° as they are funneled through valleys and around mountains. As wind streamlines are compressed by flowing through narrowing valleys, over hills and ridges, or around shoulders, the wind velocity increases. In the lee of mountain ridges or even relatively small hills (~30 m above surrounding terrain), a turbulent wake develops rotor eddies that can have strong vertical velocities. This type of high-velocity turbulent flow is often responsible for wind damage on lee slopes. Areas of high topographic susceptibility to windthrow are summarized as follows:

Rounded Hills: The flanks, particularly sloped terraces, lateral lower and middle slopes, and the lower lee side slopes are more susceptible because of increased velocity and turbulence. There is also high susceptibility on the leeward side of a rounded hill, especially where the relief rises again behind the hill.

Mountain Ridges: When wind flow is parallel to the slope, the speed and turbulence are highest near the lower slopes. When wind is at an oblique angle to the slope (20-50°), the flow becomes turbulent at mid-slope and often changes direction. When the flow is perpendicular to the slope, the velocity increases from the lower to the upper slopes and the speed is highest at the summit. Immediately behind the summit, wind velocity abates, but lee waves create high turbulence where the mixing zone reattaches to the surface relief. The most susceptible areas behind steep leeward slopes may be over sloping leeward terraces, over the plain immediately behind the leeward slope of the ridge, or over the windward slope of the next hill.

Valley Bottoms: When wind flows along or up a valley, the streamlines are condensed and the flow velocity increases near the valley bottom. Narrow valleys cause wind speeds to increase (much like a venturi) more than wide valleys do, particularly if they become increasingly narrow and rise in elevation. Valleys incised into a plateau can also be particularly windy if oriented in the direction of the wind.

Shoulders: Secondary ridges that protrude at right angles act in a similar manner to rounded hills. The upper windward slopes, crest, and lee slopes exhibit the highest wind speeds and turbulence and hence are at greatest risk.

Saddles: Saddles act as narrow valleys that compress the wind streamlines and cause the wind to accelerate considerably. These topographic features appear to affect wind flow over a wide range of scales. The valley bottoms in high-elevation passes are prone to windthrow. The lee slopes of steep ridges are also at higher risk. Windthrow hazard is often higher on moderate to steep slopes than on flat terrain or gentle slopes, although there is mixed evidence for this observation. Often there are confounding influences of poor root anchorage and wind in certain topographic positions, and it is hard to discern which factor contributes more to the windthrow hazard (e.g. wet sites in valley bottoms, or shallow soils on ridge crests). The orientation of a cutting boundary can have a greater effect on windthrow hazard than the lee or windward character of a particular slope.

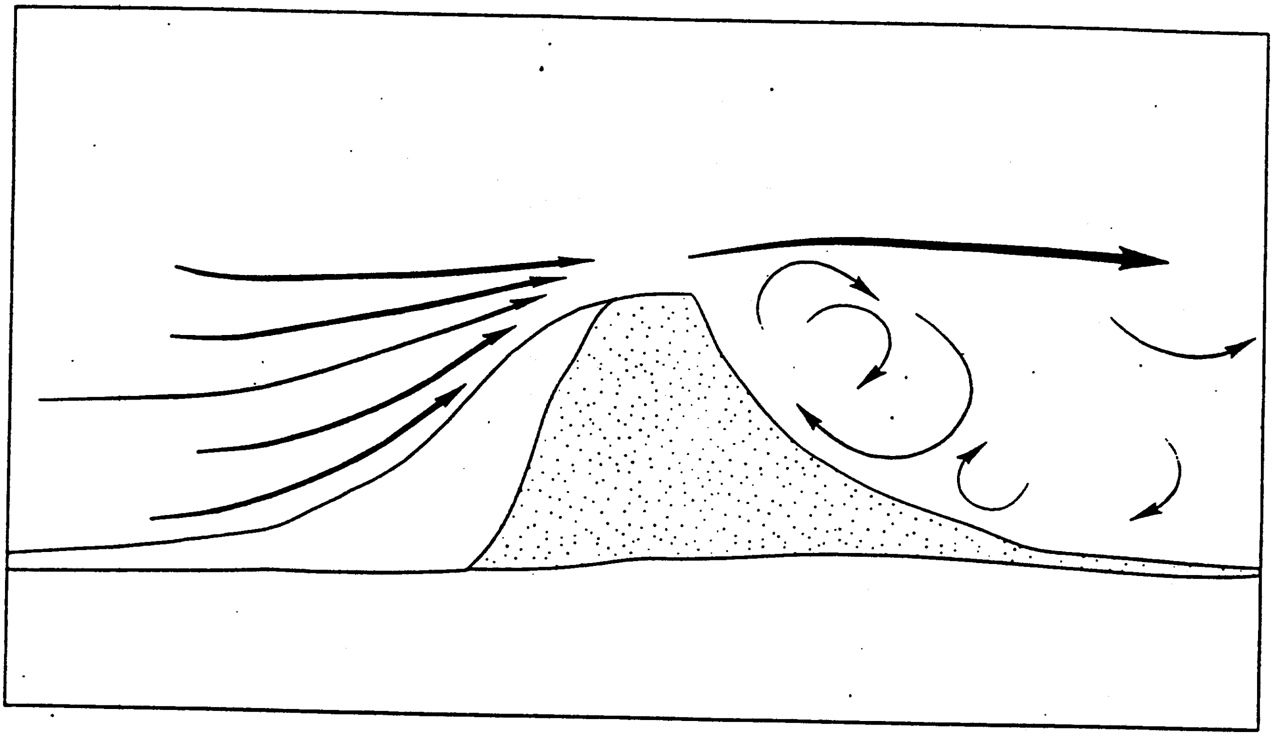

FIGURE 7. Wind flow over a hill showing flow acceleration on the windward slope and turbulence (roller eddies) on the leeward slope. (Source: After Ruel, 1992.)

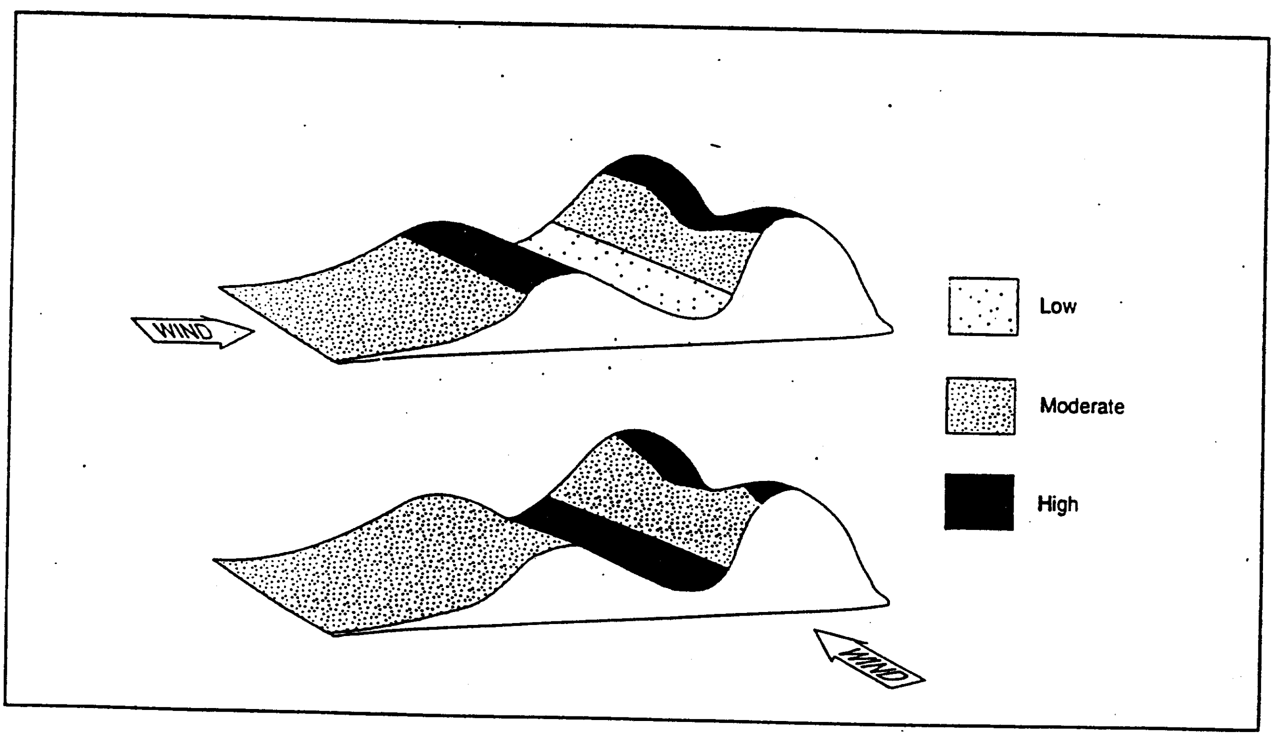

FIGURE 8. The effects of topography on wind speed. When the wind direction is perpendicular to a ridge the wind speed is relatively low in the valley bottom and increases to a maximum at the ridge top. When the wind direction is parallel to a ridge higher wind speeds occur in the bottom of the valley and near the ridge crest. (Source: After Alexander, 1987.)

4.5 Meteorological Conditions

Meteorological conditions affect windthrow through the effects of:

- wind speed, gustiness, and storm duration
- soil moisture conditions
- snow and rain loading on the crown.

Few trees are strong enough to withstand mean wind speeds in excess of 30 m/s (~100 km/hr) for more than about 10 minutes, yet considerable windthrow can occur in some stands at wind speeds of only about 15-17 m/s (~50-60 km/hr). Prolonged storms allow more time for a swaying bole to break roots and loosen root anchorage. Windthrow is often more severe during storms when the soil has been wet by previous heavy rainfalls because of the resultant reduction in root-to-soil adhesion and soil shear strength. Snow or ice loading on the crown can also increase windthrow susceptibility through the effects of increased canopy mass and an increase in the drag coefficient.

Complex terrain and surface drag resulting from a heterogeneous canopy or openings in the canopy can induce considerable turbulence in the wind flow. Wind gusts that cause windthrow often occur in bands that range from 10-250 m wide. They occur repeatedly during storms lasting several hours and have speeds ranging up to 50% higher than the mean wind flow at the surface. Gusts at the surface can have speeds comparable to that of the bulk flow 1000 m higher.

In British Columbia, most of the strong winds that cause windthrow are associated with the passage of fronts that originate in the Pacific Ocean or in the Arctic. Gale-force winds occur regularly during the winter, spring, and fall. Hurricane-force winds are not uncommon in more exposed locations. Strong winds associated with thunderstorm activity can also cause windthrow during the summer.

The strongest winds typically blow in a southeast or northwest direction on the coast. In the interior regions strong winds occur more commonly from the north, south, and west than from the east. Local terrain plays a considerable role in modifying the wind direction and speed in the interior, particularly in mountainous regions. The wind direction can shift by up to 90° as wind is funneled through a valley. Areas where two or more valleys converge can be more difficult to manage because they can experience strong winds from both valleys.

Suggested Reading

Individual tree factors: Alexander (1964), Blackburn (1983), Cremer et al. (1982), Hubert (1918), Hutte (1968), Petty and Swain (1985), Smith and Weitknecht (1915).

Stand factors: Alexander (1964), Blackburn et al. (1988), Cremer et al. (1982), Fraser (1964), Smith et al. (1987), Somerville (1980), Ruth and Yoder (1953), Harris (1989).

Soil factors: Alexander (1964), Kennedy (1974).

Topographic factors: Alexander (1964), Gloyne (1968), Hutte (1968).

Meteorological factors: Day (1950), Fraser (1964), Gloyne (1968), Mayer (1987), Oliver and Mayhead (1974).

5 WINDTHROW HAZARD EVALUATION

A quantitative approach to determining the windthrow hazard at a particular site is not yet possible because information on the frequency and occurrence of strong winds is not available. Nor is there enough information about the response of different species, crown classes, tree heights, or stand densities to high winds. There is a danger that any classification scheme will be misleading at times because of the nature of storm winds; however, intrinsic features of sites and management practices make certain stands either more or less prone to endemic wind damage.

A windthrow hazard classification has been developed based on the premise that certain conditions control or affect the wind force acting on trees and other characteristics that affect the resistance to overturning of trees. It is the balance or lack of balance between these two factors, (wind force and resistance to overturning) that determines the windthrow hazard. Considering the interplay between these two factors may be useful when trying to develop management strategies to prevent or minimize windthrow. It is also important to understand that certain characteristics may lead toward a low windthrow hazard in one situation but to a high hazard in another situation. For instance, some dense stands may be relatively windfirm along clearcut edges, yet these same stands can be very vulnerable to windthrow when thinned.

The *wind force* acting on the soil-root system to cause overturning is influenced by:

- topographic characteristics - *exposure to and control of wind direction, velocity, and turbulence*
- stand level characteristics - *density, canopy roughness*
- tree characteristics - *height, diameter, crown form.*

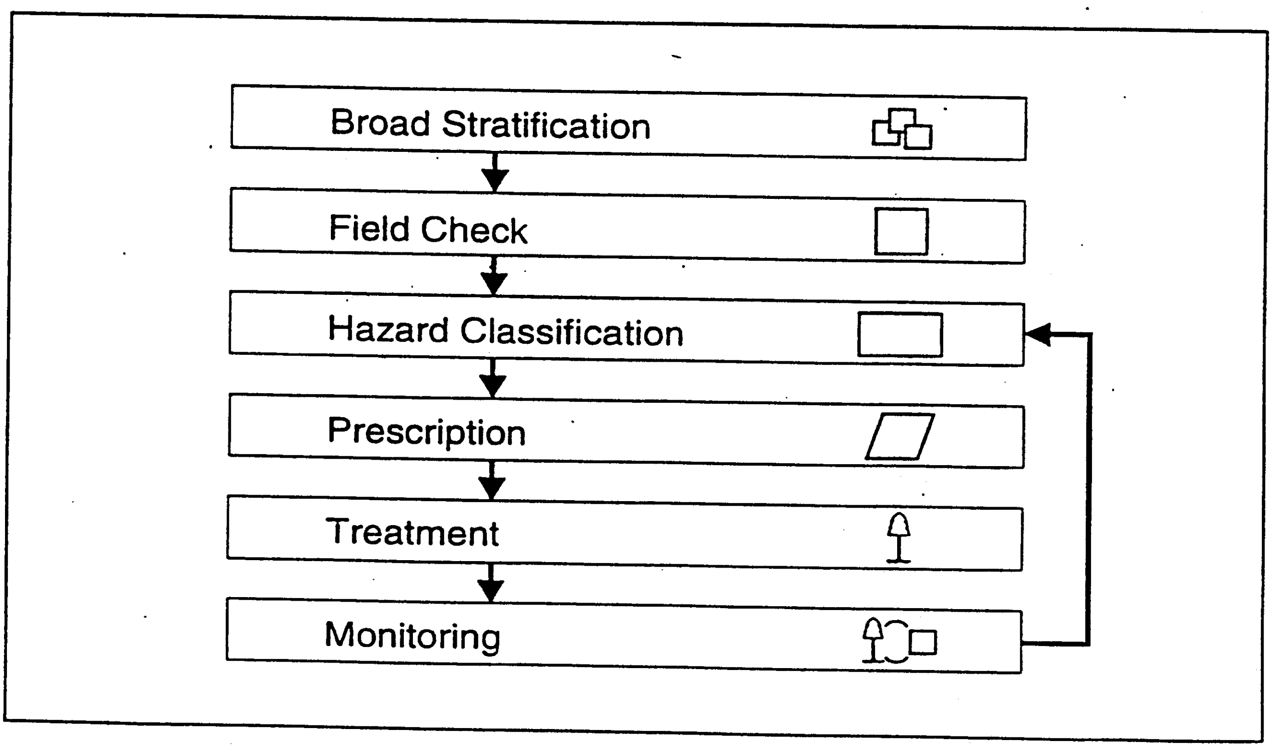

FIGURE 9. Windthrow evaluation flowchart.

Resistance to overturning is influenced by:

- tree characteristics - *rooting, bole and butt form, presence of root and butt rots*
- stand characteristics - *inter-tree damping*
- soil characteristics - *depth, structure, texture, root restricting layers, and drainage regime.*

High risk stands *(high wind force and low resistance to overturning)* are located where poor root anchorage occurs, where high wind speeds and turbulence are more likely to occur, and where the stand structure and composition and tree form make it more liable to wind damage if openings are made.

Low risk stands *(low wind force and high resistance to overturning)* are located where good root anchorage occurs as a result of soil conditions, where topographic sheltering reduces the windspeed and turbulence, and where the stand and individual tree characteristics make trees less susceptible to windthrow after openings are made.

Moderate risk stands either have factors that contribute to poor anchorage but a low wind force, moderate resistance to overturning and a moderate wind force, or good anchorage but a high wind force. The latter case may be more stable than the former.

In addition to the above, many on-site indicators can be used to refine the assessment of the windthrow hazard. Certain areas have a reputation for being particularly windy. In windy areas the forest canopy is often deformed or asymmetrical, or branches are severely abraded. Adjacent cutblock boundaries can be assessed for the incidence and orientation of windthrow. Evidence of extensive windthrow or stembreak in the natural stand before cutting suggests that windthrow is likely to occur after cutting. Evidence of pit and mound micro-topography indicates that windthrow has occurred in the past and is therefore likely to occur again. Systematic documentation of the orientation of windthrow in the natural stand can indicate the expected direction of damaging winds.

Mapping of the spatial patterns of natural or management-induced windthrow may give an indication of which topographic locations in a local landscape are most vulnerable. Road cuts in the area can be used to better determine the spatial variability of factors that might affect root anchorage. Soil pits should be used to determine rooting depth, soil depth, soil moisture regime, and other factors mentioned above that affect the resistance to overturning.

Rooting depths are best determined by excavating soil pits 1-2 m away from typical trees in the stand. Rooting depth is determined by measuring the depth from the top of the forest floor to the deepest live root, irrespective of size. If windthrown trees are present, an estimate of rooting depth may be taken from the root mass of the tree. Use of the rooting depth near the perimeter of the root mass rather than the center will likely produce a better correlation with rooting depths determined from soil pits (in some cases, rooting is deeper near the center of the root mass).

Though the site windthrow hazard is largely determined by inherent site features such as topographic exposure and rooting characteristics, the risk of windthrow can also change over time as stand structure and composition change and as management activities such as road development or adjacent cutblock locations affect wind flow and soil conditions. These dynamics should be considered in longer term management plans.

TABLE 1. Windthrow hazard evaluation

WIND FORCE FACTORS:		
HIGH HAZARD	MODERATE HAZARD	LOWER HAZARD
topographically exposed locations: crests, saddles, upper slopes, etc.		topographically protected locations
boundaries on the windward edge of a stand	boundaries parallel to the storm wind direction	boundaries on the lee edge of a stand
tall trees	trees of intermediate height	short trees
large dense crowns	moderately dense crowns	small open crowns
RESISTANCE TO OVERTURNING:		
HIGH HAZARD	MODERATE HAZARD	LOWER HAZARD
trees with low taper and no butt flare	trees with moderate taper and moderate butt flare	trees with high taper and large butt flare
shallow rooting	moderately deep rooting	deep rooting
(<0.4 m)	(0.4 - 0.8 m)	(> 0.8 m)
root rot areas	-	no evidence of root rot
shallow soils	moderately deep soils	deep soils
(<0.4)	(0.4 - 0.8 m)	(> 0.8 m)
poorly drained soils	imperfectly to moderately well-drained soils	well-drained soils
OTHER INDICATORS:		
HIGH HAZARD	MODERATE HAZARD	LOWER HAZARD
moderate to extensive natural windthrow present	minor natural windthrow present	no natural windthrow
extensive windthrow present on similar adjacent cutting boundaries	minor to moderate windthrow present on similar adjacent cutting boundaries	no windthrow on similar adjacent cutting boundaries
pit and mound micro-topography		no evidence of pit and mound microtopography

6 WINDTHROW MANAGEMENT STRATEGIES

Each windthrow hazard class has implications that might affect the feasibility and timing of management practices. On high-hazard sites, wind damage is likely to occur at some time during the rotation and should be considered carefully during the formulation of broad-scale plans and site-specific prescriptions. On moderate hazard sites, wind damage could affect the outcome of operational treatments and should be considered. On low-hazard sites, wind damage is unlikely to occur over a rotation and management for windthrow can be considered as a relatively low priority.

The objective of windthrow management strategies is to reduce the wind force acting on the crowns and to increase the anchorage strength of the soil-root systems of residual or boundary trees. This can be achieved by selecting treatment or boundary locations and orientations that favour low wind speeds and/or good anchorage and by selecting for or controlling how certain stand and tree characteristics are modified or develop over time. Using a combination of these strategies should further reduce the risk of windthrow.

6.1 Clearcutting and Protection Forests

Careful location and design of boundaries can minimize wind damage.

- Downwind boundaries (windward stand edges) should be located on sites that are at least risk. Windward stand edges should be located on deep, well-drained soils where trees are more likely to be deeply rooted. In mountainous terrain, fluvial debris flow fans often provide some of the most windfirm cross-valley boundary locations because their deep, coarse soils and well-drained character allow deep rooting. Leeward stand edges are usually quite windfirm, even when located on relatively high-hazard sites, because of the protection from the direct force of the wind that the upwind stand provides. If possible, cutblocks should be oriented with any long-axis in the direction of the storm winds.
- Utilize natural landscape boundaries to create windfirm edges (e.g. rock bluffs, bogs, non-merchantable timber, landslides or snow avalanche tracks).
- Avoid locating clearcut boundaries in areas that have evidence of previous extensive or chronic windthrow.
- If a windward stand boundary proves to be windfirm, adjust logging plans so that it is not logged in the short-term. Most endemic windthrow occurs in the first three years after cutting. Try to replicate the conditions on these boundaries to create additional windfirm boundaries.
- Stand edges should be left relatively uniform and smooth. They should not have sharp corners or indentations that are exposed to the wind.
- Avoid damaging the structural roots of trees along opening boundaries during falling and ground skidding operations and during backspar trail and road construction.
- Stand edges may need to be feathered to reduce windthrow incidence on high and moderate hazard sites. The goal of feathering is to selectively remove vulnerable trees along opening boundaries, leaving the more windfirm stems to protect the downwind stand. More than 15-20% of the total number of trees should not be removed. Excessive thinning will increase canopy roughness and result in greater energy transfer into the canopy, thus increasing the risk of windthrow. Similarly, as tree-to-tree contact tends to damp the sway period created by wind, excessive thinning will reduce this damping effect. (See Section 6.2).
- If possible, include poorly drained areas within an opening. Alternatively leave a buffer of well-drained soils between the poorly drained soils and the opening edge. Treat areas of shallow soils and other high-hazard sites in a similar fashion.
- If windthrow occurs along an opening boundary, do not simply salvage the windthrow and establish a new boundary with the same topographic, soil and stand conditions. Re-establishing

the conditions that resulted in windthrow in the first place will likely lead to further windthrow. Consider leaving the windthrown area as a protective buffer for the timber behind, especially if the windthrow appears to have stabilized. A boundary that is 3-4 years old and shows no evidence of fresh windthrow can usually be considered stable. Take advantage of the natural feathering which has occurred by removing only downed or damaged material. Alternatively, look for changes in topographic, soil or stand conditions that may result in a more windfirm situation, then establish a new boundary at that location.

- Establish a windfirm boundary and from that point, log progressively into the wind. This approach may be used at more that one location in an area so that the cut is well dispersed.
- Extensive areas of high windthrow hazard may require the progressive development of cutblocks to minimize exposure and to facilitate salvage of windthrown timber.
- If possible, openings, roads and trails should be located in such a way that when windthrow occurs, it can be salvaged with as little damage as possible to regeneration.
- Narrow leave blocks between openings tend to be vulnerable to windthrow. Widths on the order of 500 m or more are suggested.
- Deciduous types tend to be more windfirm than conifers provided that they are not over mature. They are often in a leafless condition during the windier seasons.
- Clearcutting or not cutting may be the most appropriate treatments for high hazard stands which contain current endemic windthrow. Whenever possible, avoid putting boundaries in these areas. It may be possible to use silvicultural systems other than clearcutting in second growth stands on high-hazard sites if these stands are thinned at an early age to develop their windfirmness.

6.2 Edge Stabilization Treatments

- Edge feathering can be used to reduce the drag force on boundary trees. Trees within the edge buffer should be removed in the following order of preference:
  1. Unsound trees, especially if they have a large crown. These include diseased, deformed, forked, scarred, mistletoe infested, and root rot infested trees.
  2. Trees with asymmetric or stilt roots.
  3. Trees growing on unstable substrates, e.g., rocky knolls, large boulders, nurse logs, poorly drained depressions.
  4. Tall non-veteran trees, especially with the above features or with disproportionately large crowns.
- Residual trees should be left in the following order of preference:
  1. Sound, well-rooted veterans (e.g. snag-top cedars) or deciduous trees.
  2. Sound trees (strong roots and good taper) with relatively small, open crowns.
  3. Sound snags, when safety is not compromised.
- Stem removal should not exceed 15-20% of the trees in a strip 20-30 m in from the edge of the stand. Excessive thinning will increase windthrow susceptibility. Edge thinning is not recommended in single-storied, high density stands.
- Topping and/or pruning (limbing) of vulnerable trees along opening boundaries may be necessary to protect and maintain critical areas such as streamside buffers, ungulate ranges, forage areas, and other critical wildlife habitat.
- Reducing the crown by 20-30% appears to be adequate to reduce the risk of windthrow for most trees.
- A combination of edge-feathering and topping or pruning may be quite effective in high hazard areas.

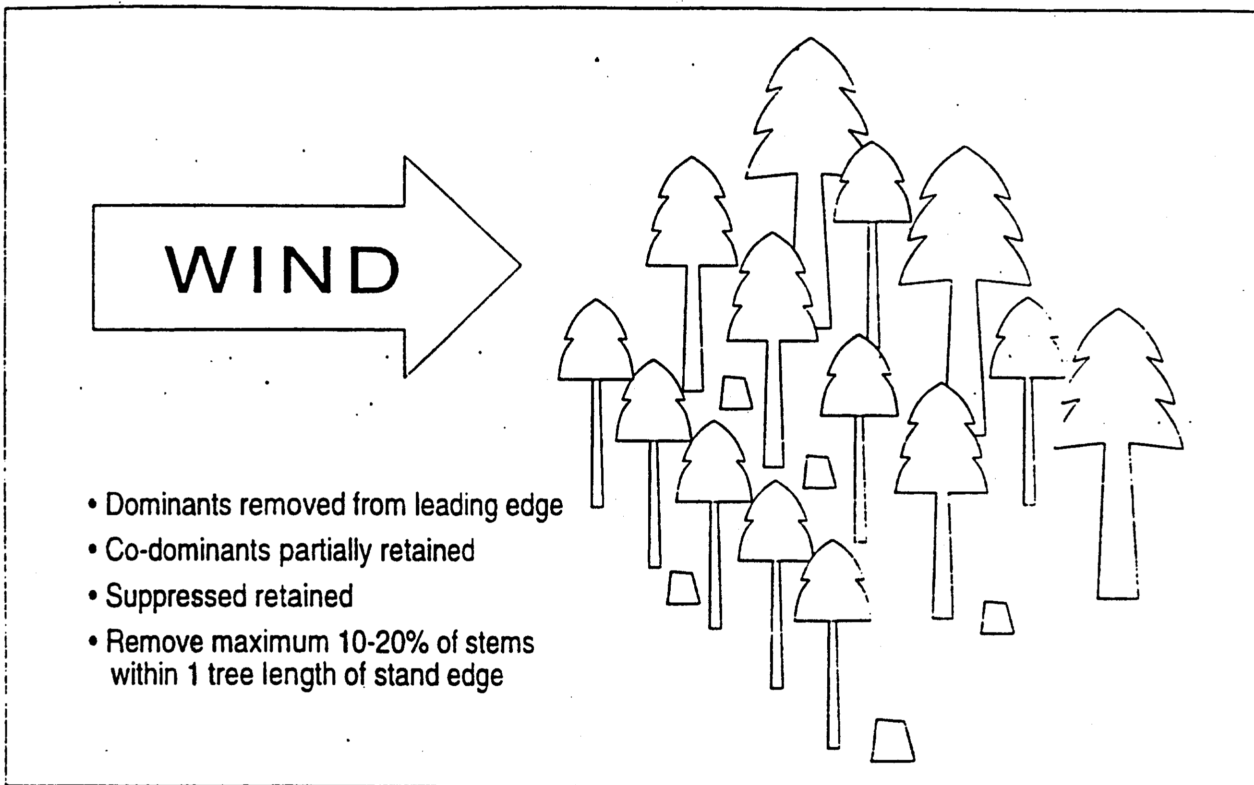

FIGURE 10. Edge feathering techniques in a multi-storied stand to stabilize the boundary of an opening.

6.3 Partial Cutting and Commercial Thinning

Partial cutting and commercial thinning treatments that open the canopy increase the drag force on individual trees and consequently increase their risk of overturning. They should be used cautiously on high and moderate windthrow hazard sites. The amount of canopy removal should also reflect the windfirmness of the original stand. Windfirm trees should be preferentially retained.

- ◆ When using group selection or strip cuts ensure that all high-hazard areas (e.g. poorly drained areas, areas of shallow soils, root rot pockets) are either completely logged or adequately buffered. These systems should be used with caution in high hazard zones.
- ◆ When leaving small groves or patches of timber, ensure that they are located on deep, well-drained soils or other sites where the windthrow hazard is low.
- ◆ Thin from below in uniform shelterwood cuts and commercial thinnings. Where possible avoid creating gaps greater than about one half tree length in these kinds of cuts.
- ◆ Avoid locating selection cuts, shelterwood cuts, or commercial thinnings at clearcut edges, especially if poorly drained soils, shallow soils or other high hazard conditions are present. Leave an untreated buffer between the opening and the treatment unit.
- ◆ When using selection or shelterwood systems on high-hazard sites, no more than 15-20% of the basal area should be removed in the initial harvest. The most vulnerable stems should be removed first, especially those with disproportionately large crowns or poor rooting conditions. Where initial stand densities are high, ensure that the opportunity for branch-to-branch contact between trees is maintained so that stem sway periods are damped.

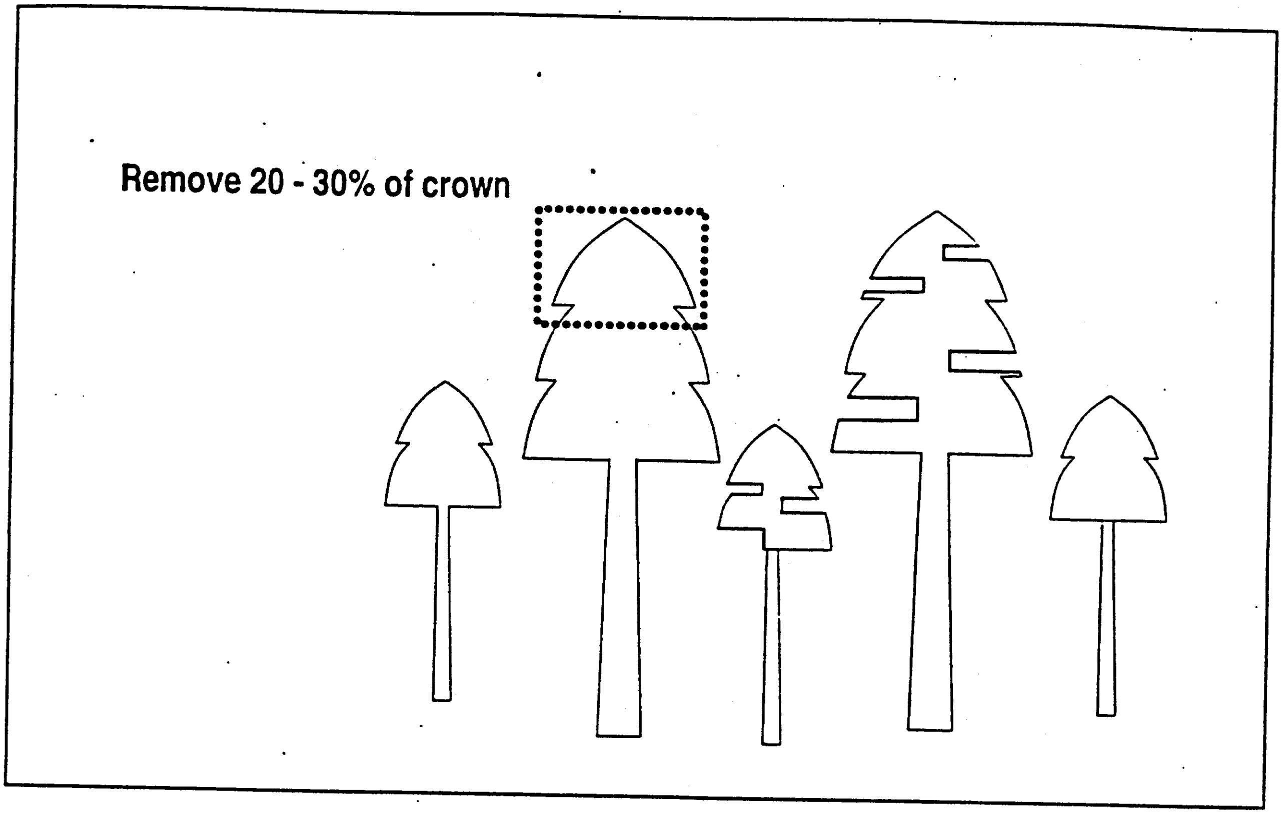

FIGURE 11. Topping and spiral pruning to reduce the wind force on boundary trees that have a high windthrow hazard.

- Commercial thinning should be avoided on high-hazard sites, particularly in very dense stands. If it is necessary, thin from below in a series of low intensity entries to reduce the probability of wind-related damage.
- Heavy commercial thinning of stands taller than 15-20 m is likely to result in considerable windthrow on high hazard sites. Late thinning should probably be done lightly, if at all on these sites.
- Trees with root systems damaged during yarding should be removed if their windfirmness is questionable.
- If windthrow occurs within a partial cutting treatment, reevaluate the windthrow hazard of the remaining trees within the stand before making the decision whether to 1) clearcut the stand, 2) salvage the windthrow and the remaining vulnerable stems, or 3) leave the windthrow. Removing or leaving windthrown timber will have other impacts that must be considered.

6.4 Regeneration and Stand Tending Treatments

Regeneration should be established on stable substrates on high-hazard sites. Trees growing on unstable substrates such as logs and old stumps should be preferentially removed during spacing. Some European research suggests that maintaining a deciduous component may improve the windfirmness of the surrounding conifers.

- Early spacing on moderate-to-high hazard sites will tend to promote windfirm stands in the long term. Alternatively, a dense stand can be maintained throughout the rotation.

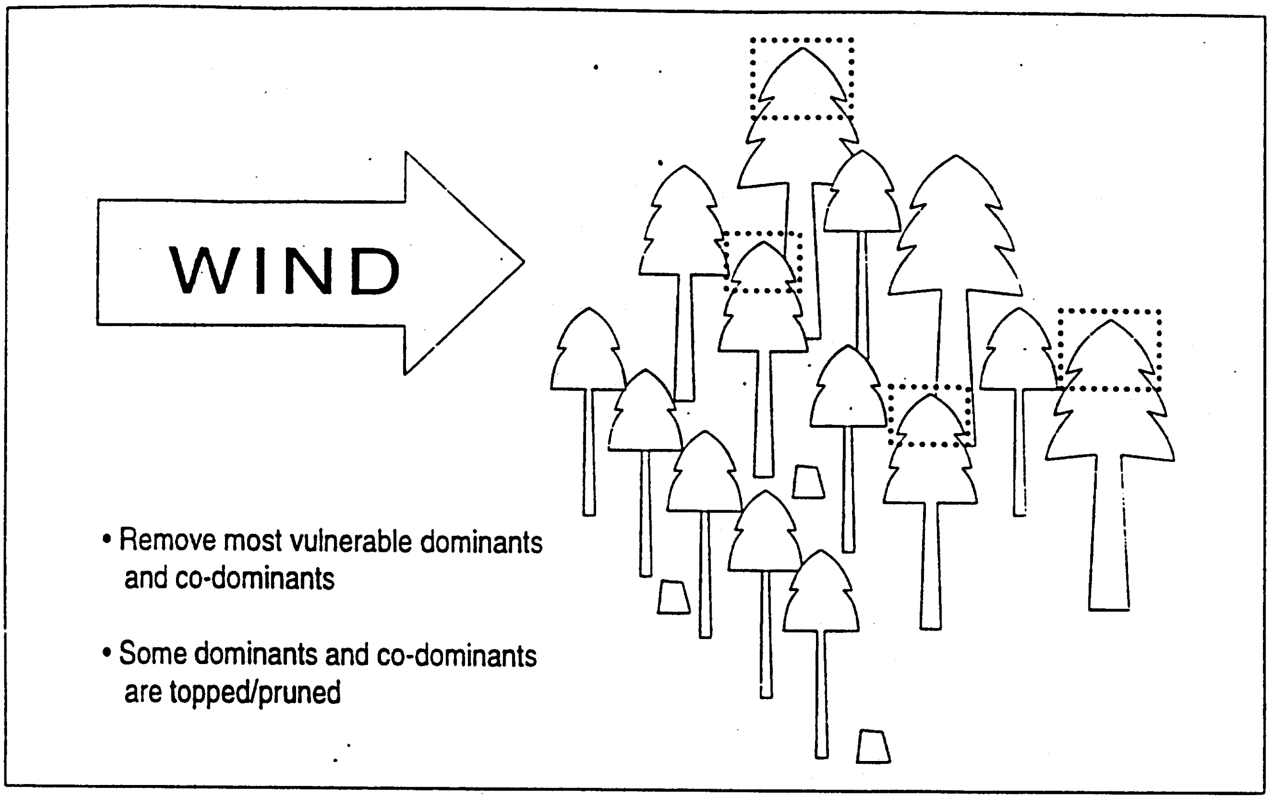

FIGURE 12. Edge feathering and topping to stabilize a high windthrow hazard boundary.

- ◆ A series of light-intensity spacings or thinnings should be used on high-hazard sites rather than a single, heavy treatment. A period of several years should be left between each entry so that the residual stand has an opportunity to adapt to the new wind regime created by the spacing/thinning treatment.
- ◆ Some European research has indicated that fertilization immediately following late thinning treatments has resulted in increased windthrow. If this occurs the suggested solution is to delay fertilizing for several years following thinning to allow windfirmness to develop.
- ◆ Ditching and draining wet sites should be considered as a means of improving soil conditions and root anchorage on high hazard sites. Site preparation treatments which result in weak rooting and poor anchorage should be used with caution on high hazard sites.
- ◆ In high hazard areas where windthrow is severely damaging immature forests it may be necessary to develop harvesting schedules that are based upon the height of the dominant trees in the stand. This is becoming an accepted practice in some areas of the United Kingdom.

There are three basic strategies for regenerating windfirm stands on high to moderate windthrow hazard sites. These range from:

1. growing trees at a *wide spacing* to develop the natural windfirmness of each tree. This may result in knotty, low-density wood, but it may be a suitable strategy for sites where any type of forest cover is adequate (e.g. at very high elevations).
2. growing trees at a *medium spacing* either by planting at a medium density or using early thinning to promote windfirmness. The stand should not be thinned after the height exceeds 15-20 m. This will allow the canopy to close and increase the windfirmness of the stand during its more vulnerable older stage.

3. growing trees at a *close spacing* and harvesting at the onset of windthrow or at a specified height (e.g. 20 m) when the risk of windthrow approaches a critical threshold. These stands should not be thinned at any age because of the increased risk of windthrow.

6.5 Windthrow Monitoring

The objective of monitoring windthrow is to provide managers with feedback so that they may improve the hazard classification and refine treatment techniques. It is suggested that the broad scale maps used for the initial Hazard Evaluation be updated annually to show new windthrow. Major windthrow events should be documented by noting the date of the event, the peak wind speed and direction, and the rainfall recorded at the nearest climate station. A subsample of recent blocks from each of the strata identified on the broad scale map should be surveyed each year. A sampling method and sample field data form is provided at the back of this handbook.

7 SUMMARY

Windthrow is a natural process in forests and no forest or cutting unit will ever be completely immune from wind damage because of the nature of storm winds. Certain sites are inherently more prone to windthrow, either because of greater topographic exposure to damaging winds, poor root anchorage, or a more susceptible stand structure and composition. Losses resulting from windthrow can be significantly reduced by recognizing sites where it is likely to be a problem and using management practices to minimize its impact.

This guide provides only a brief synopsis of the literature on windthrow. The hazard classes are qualitative and only intended to serve as guidelines for stratifying high-risk from low-risk sites. More quantitative approaches will be developed as more information becomes available on the characteristics of tree rooting strength under different soil conditions and through wind tunnel and field studies on the effects of landscape and stand characteristics on wind flow and force on tree canopies.

APPENDIX 1. Windthrow monitoring procedures and data forms

Windthrow monitoring procedures

Clearcut edges

Divide the perimeter of an opening into 15-30 segments of equal size. Randomly locate a 0.05 hectare (12.6 meter radius) circular lot in each segment. The outside edge of the plot should touch the original opening boundary. Record plot location, soil, topographic and standing tree characteristics. Record the attributes of any windthrow or windsnap whose point of germination is in the plot (see sample data sheet below).

Partial cuts

Two alternative monitoring systems are offered. For units with detailed timber cruise and soils maps and data, it may be necessary only to record the attributes and location of windthrow. Systematically locate strip plots 10 meters wide across the full width of the unit. Orient the strips so that they are non-parallel to slope and prevailing storm wind direction. Existing cruise strips may make good centerlines. Record strip length. Tally, map and record the attributes of any windthrow or windsnap whose point of germination is in the strip.

Alternatively, systematically locate 0.05 hectare circular plots ensuring good coverage of the unit. Record soil, topographic and standing tree characteristics. Record the attributes of any windthrow or windsnap whose point of germination is in the plot.

WINDTHROW HAZARD EVALUATION - EXAMPLE FIELD CHECKLIST

District: ____________________ Licence: ____________________ C.P.: __________ Block: ______

Boundary Section: ______________________________________ Surveyor: ________ Date: ______

Wind Force Indicators

Topographic Exposure:

- ☐ Crest
- ☐ Saddle
- ☐ Upper Slope
- ☐ Shoulder
- ☐ Bowl
- ☐ Valley bottom perpendicular to prevailing winds

Boundary Orientation:

- ☐ Windward
- ☐ Sub-parallel
- ☐ Lee

Stand Attributes:

- ☐ Uniform - high density
- ☐ Uniform - moderate density
- ☐ Uneven - high density
- ☐ Uniform - low density
- ☐ Uneven - low density
- ☐ Uneven - moderate density

- ☐ Taller than average
- ☐ Intermediate
- ☐ Shorter than average

Tree Attributes:

- ☐ Taller than average
- ☐ Average
- ☐ Shorter than average

- ☐ Large dense crowns
- ☐ Moderately dense crowns
- ☐ Small open crowns

Overturning Resistance Indicators

Tree Attributes:

- ☐ Low taper
- ☐ Moderate taper
- ☐ High taper

- ☐ No butt flare
- ☐ Moderate butt flare
- ☐ Large butt flare

- ☐ Root or stem rot
- ☐ No root or stem rot

Rooting Depth:

- ☐ Shallow (<0.4 m)
- ☐ Moderately Deep (0.4-0.8 m)
- ☐ Deep (>0.8m)

Soil Drainage:

- ☐ Poor
- ☐ Imperfect
- ☐ Moderate
- ☐ Good

Other Indicators

Windthrow in stand:

- ☐ Extensive
- ☐ Moderate
- ☐ Minor
- ☐ None

Windthrow along adjacent edges:

- ☐ Extensive
- ☐ Minor
- ☐ Moderate
- ☐ None

Pit and mound microtopography:

- ☐ Extensive
- ☐ Minor
- ☐ Moderate
- ☐ None

Windthrow Hazard Class

- ☐ High
- ☐ Moderate
- ☐ Low

WINDTHROW MONITORING - EXAMPLE PLOT CARD

District: ____________ Licence: ________ C.P.: ______ Block: ________

Boundary Section: ____________ Plot Size: ________ Surveyor: __ Date: ________

Plot #:									
Boundary Shape:									
Boundary Aspect:									
Valley Orientation:									
Plot Aspect:									
Plot Slope:									
Plot Elevation:									
Slope Position:									
Eco. Association									
Soil Texture									
Rooting Depth:									
Depth impeding layer:									
Type impeding layer:									
#Standing Trees:									
Snag									
Veteran									
Dominant									
Co-dominant									
Intermediate									
Suppressed									
% Species Composition									
#Windthrown Trees									
Snag									
Veteran									
Dominant									
Co-dominant									
Intermediate									
Suppressed									
% Species Composition									
Direction of Fall									
#Windsnapped Trees									
Snag									
Veteran									
Dominant									
Co-dominant									
Intermediate									
Suppressed									
% Species Composition									
Direction of Fall									
Root Rot									
Bark Beetle									
Windthrow Hazard Class									

Comments:

WINDTHROW HANDBOOK - FEEDBACK

The authors would appreciate your feedback on the usefulness and clarity of the material contained in this handbook. Please take a moment to fill out this questionnaire and send it to the address provided below.

Your comments will enable us to expand and improve future editions.

Section	Was this section useful			Could its clarity be improved		Your suggestions please
						(Please use back if you need more space)
1.0	Yes	Somewhat	No	Yes	No	
2.0	Yes	Somewhat	No	Yes	No	
3.0	Yes	Somewhat	No	Yes	No	
4.0	Yes	Somewhat	No	Yes	No	
4.1	Yes	Somewhat	No	Yes	No	
4.2	Yes	Somewhat	No	Yes	No	
4.3	Yes	Somewhat	No	Yes	No	
4.4	Yes	Somewhat	No	Yes	No	
4.5	Yes	Somewhat	No	Yes	No	
5.0	Yes	Somewhat	No	Yes	No	
6.0	Yes	Somewhat	No	Yes	No	
6.1	Yes	Somewhat	No	Yes	No	
6.2	Yes	Somewhat	No	Yes	No	
6.3	Yes	Somewhat	No	Yes	No	
6.4	Yes	Somewhat	No	Yes	No	
6.5	Yes	Somewhat	No	Yes	No	
7.0	Yes	Somewhat	No	Yes	No	
8.0	Yes	Somewhat	No	Yes	No	
9.0	Yes	Somewhat	No	Yes	No	

Figure	Was this figure useful			Could its clarity be improved		Your suggestions please
1	Yes	Somewhat	No	Yes	No	
2	Yes	Somewhat	No	Yes	No	
3	Yes	Somewhat	No	Yes	No	
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5	Yes	Somewhat	No	Yes	No	
6	Yes	Somewhat	No	Yes	No	
7	Yes	Somewhat	No	Yes	No	
8	Yes	Somewhat	No	Yes	No	
9	Yes	Somewhat	No	Yes	No	
Table	Yes	Somewhat	No	Yes	No	
10	Yes	Somewhat	No	Yes	No	
11	Yes	Somewhat	No	Yes	No	
12	Yes	Somewhat	No	Yes	No	

Please send form to:

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GLOSSARY

Damping: dissipation of energy in a tree through movement and contact of branches, foliage, stem, and roots.

Drag: friction caused by trees and surface features in the boundary layer.

Drag Coefficient: a coefficient that relates the amount of force intercepted by the canopy to the windspeed or the effectiveness with which momentum is transferred (downwards) across a turbulent boundary layer.

Shear Stress: a measure of the tendency for one part of a solid to slide past another. Units: N/m^2.

Shear Strain: the angle through which material is distorted as a result of shear stress. Units: dimensionless.

Streamline: a line that indicates the direction of flow.

Stress: force applied per unit area. Units: Newtons per square meter (N/m^2).

Strain: the change in length that occurs under a given stress. No units.

Static Force: a constant force applied to a body.

Sway Period: the amount of time required for a tree crown to move through a complete sway.

Sway Amplitude: the distance that the tip of the crown moves from the vertical to its outermost sway point.

Toppling: when a tree leans by pivoting around a point below-ground; different from windthrow where roots are torn from the ground.

Uprooting: when a tree falls with most of its larger roots intact, tearing up the soil in the process.

Stembreak: when a strong wind snaps the bole of a tree rather than uprooting it. *Synonym*: windbreak, windsnap.

Windfirmness: the ability to resist overturning. A function of both crown and rooting characteristics.

Windthrow: same as uprooting. *Synonyms*: windfall, windbreak, blowdown, windblow - imply that the cause of overturning is related to strong wind.

Windthrow Hazard: the susceptibility of a stand to endemic windthrow (by gale force winds that have a recurrence interval of 5-10 years).

Windthrow Risk: the probability of wind causing damage to a stand.

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WINDTHROW HAZARD ASSESSMENT AND MANAGEMENT IN RIPARIAN MANAGEMENT AREAS IN COASTAL BRITISH COLUMBIA

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ABSTRACT

Windthrow damage to riparian management areas is a concern in many areas of coastal British Columbia. Under the recently enacted Forest Practices Code of BC Act, lakes and streams must be classified and management areas of specific widths are required. For example, fish bearing creeks from 1.5 to 5 meters wide require 20 meter wide riparian reserves plus 20 meter wide management zones to buffer the reserve. In response to these new requirements a variety of management options are being developed in coastal BC. The 'Windthrow Handbook for BC Forests' outlines procedures for pre-harvest assessments of windthrow hazard. Feathering of management zones is being used in multi-story stands with low or moderate windthrow hazard. In areas determined to have high windthrow hazard, topping, and pruning techniques are being tested. A recent innovation is the use of a helicopter suspended shearing bar to remove the top branches from trees. This is a safe, inexpensive technique for directly treating reserve zone trees and has won support from licensee and agency representatives in the locations where it has been applied. Research into the long term effectiveness of topping and feathering treatments is underway.

INTRODUCTION

Maintaining residual streamside vegetation is desirable to provide shade, a supply of leaves and insect drop, visual cover, bank stability, large organic debris, and reduction of logging debris and sediment entry into streams (Toews and Brownlee, 1981). Streamside reserves also provide habitat for bird and wildlife species and improve the visual appearance and recreational value of managed forest land. Wind damage to partial or fully forested streamside strips has occurred frequently in coastal BC (Moore, 1977). Windthrow is commonly cited as a management concern by forest managers and serious wind damage to riparian reserves disrupts the planning process (Mitchell, 1995a). Post-harvest windthrow can lead to partial or total loss of the beneficial effects of the forest canopy, entry of large quantities of branches and stems into the stream channel, over-turning of rootwads and increased sedimentation. Windthrow salvage is costly and dangerous and may result in further damage to stream banks. Unsalvaged windthrow can provide rearing habitat for bark beetles.

FOREST PRACTICES CODE

Under the Forest Practices Code of BC Act enacted in 1995, streams are classified based on use by fish and channel width. The 'riparian management area' consists of an inner 'riparian reserve zone' and an outer 'riparian management zone'. Where reserve zones are required, it is intended that they be disturbed as little as possible by management activities. The management zone buffers the reserve zone. Table 1 summarizes the stream classes

FOREST-FISH CONFERENCE, CALGARY MAY 1-4, 96

Stream Width (m)	Fish Stream	Stream Class	Riparian Reserve Zone Width (m)	Riparian Management Zone Width (m)	Riparian Management Area Width (m)
>20	yes	S1	50	20	70
5-20	yes	S2	30	20	50
1.5-5	yes	S3	20	20	40
<1.5	yes	S4	0	30	30
>3	no	S5	0	30	30
<3	no	S6	0	20	20

Table 1. Stream classes, riparian reserve zone and riparian management zone widths.

and the associated reserve and management zone widths (BCMOF, 1995). The 'best management' approaches for each stream class are summarized in the Riparian Management Area Guidebook (BCMOF & BCMOE, 1995). Where modifications to the management zone or reserve zone widths set out by legislation are proposed due to concerns about windfirmness, they must be supported by a windthrow hazard assessment. The Gully Assessment Procedure Guidebook (BCMOF & BCMOE, 1995) contains a summary of pre-logging management strategies for various classes of forested gullies. On gullies with moderate or high downstream impact potential and high or moderate water transport, fan destabilization, or debris flow initiation potential, suggested management strategies include leaving the gully unlogged and buffered. The guidebook underlines the need for windfirm boundaries in cases where treed gully reserves are left.

ASSESSING WINDTHROW HAZARD

There is to date no officially approved method for windthrow hazard assessment in BC. The Windthrow Handbook for BC Forests (Stathers et al, 1994) summarizes windthrow concepts and management strategies and lays out a checklist of windthrow hazard indicators. A simple framework for relative windthrow hazard classification called the 'Windthrow Triangle' based on the assessment of topographic exposure, soil properties and stand characteristics and the interpretation of past windthrow activity is presented in Mitchell (1995b). This approach has been adopted for the purpose of instructing practitioners, and is being been tested in current studies. Key indicators of high windthrow hazard for riparian management areas include shallow rooting, poor drainage, high pre-harvest stand density, high topographic exposure due to funneling or speed up of winds. Windthrow is more likely where leave strips are perpendicular to wind flow (Moore 1977).

The Riparian Management Area Guidebook contains strategies for improving the windfirmness of riparian management areas, including placement of boundaries in more windfirm locations and avoidance of boundary indentations or projections. Where moderate or high windthrow hazard is determined, managers can vary from the 'best treatment' options in the guidebook. Alternative treatments currently being used in coastal BC include: full retention of both management and reserve zone trees; partial retention or feathering of management zone trees to buffer reserve zone trees; removal of trees from the management zone combined with topping or top-pruning of reserve zone trees; and complete removal of overstory

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from both the management and reserve zones. Complete removal of the overstory may be accompanied by understory or safe snag retention. The choice between alternative treatments is made in consideration of potential impacts with and without treatment, and in consultation with Ministry of Forests and Ministry of Environment staff.

EDGE FEATHERING

The objective of edge feathering is to increase the permeability of upwind stand boundaries to wind so that wind speed up at canopy height is reduced. Edges recently exposed by harvesting behave in one of three ways, they remain undamaged, they are partially damaged within a tree length or two of the edge (natural feathering) or they are heavily damaged for several tree lengths (progressive damage). Pre-feathering management zone edges during harvesting should be considered where there is evidence that harvesting boundaries with similar characteristics undergo natural feathering. The objective in feathering is to remove the trees with the lowest windfirmness. Trees with asymmetric or stilt roots, trees which are rooted on unstable substrates like old logs or rootwads are typically less windfirm. Veterans or trees with broken tops are often more windfirm (Stathers et al., 1994). Feathering is unlikely to be effective where progressive windthrow has occurred on adjacent harvesting boundaries with similar characteristics. In these situations removal of management zone trees and topping or top-pruning of reserve zone trees should be considered. A cooperative project between the University of BC, Ministry of Forests Vancouver Region and Western Forest Products Limited is underway to measure the properties of old edges in the field and to model the behaviour of feathered edges in a wind tunnel.

TOPPING AND TOP-PRUNING

Tree topping and branch pruning are arboricultural practices which have long been used for improving the windfirmness of individual trees in urban applications. These practices have recently been extended to forestry practice in coastal BC in an attempt to preserve riparian and gully reserve trees in high hazard areas. During 1995, the Vancouver Forest Region of the BCMOF, Western Forest Products Limited and the Forest Engineering Institute of Canada cooperated in a study of manual and aerial topping and pruning techniques in a streamside reserve on northern Vancouver Island (Boswell, 1995). Subsequent experimentation has lead to the development of an inexpensive helicopter branch shearing technique which has been used operationally on a number of riparian and gully reserves (Aldersey, 1995). With this technique the branches from the upper 30% of the crown of dominants and codominants within the reserve zone are removed using a passive shearing bar suspended below the helicopter. In second growth stands with branch base diameters less than 10cm, costs of approximately $35-$45 per treated tree are typical.

CONCLUSION

The Forest Practices Code requirements for enhanced riparian and gully management have lead to an increased need for windthrow assessment and management in BC. In response to recurrent losses of riparian reserves, a variety of management techniques are being applied. A number of cooperative research projects are being initiated under Forest Renewal BC funding to investigate the long term effectiveness of these techniques.

APPENDIX 11-7

APPENDIX 11-7

Definition excerpted from "Forests and Fish Report" dated February 22, 1999

"Channel migration zone" means, for each of the types of streams described below, the area where the active channel of such stream is prone to move and where such movement would result in a potential near-term loss of riparian forest adjacent to the stream. For purposes of this Report, "channel migration zones" are associated with moderately confined streams, unconfined streams, unconfined meandering streams, unconfined braided streams, and unconfined avulsing streams. As used in this Report, no "channel migration zone" will be associated with any other waters of the state. A chart summarizing the following discussion is attached as Schedule A-2. The Forest Practices Board Manual will provide further guidance for the delineation of channel migration zones on the ground. Unstable slope protections for inner gorges and outer bends of meandering streams as provided in Appendix C are potential supplements to channel migration zone riparian protections.

(i) <u>Moderately confined streams defined</u>. As used in this definition, "moderately confined streams" are typically 3rd or 4th order Type F or S waters with bankfull widths of less than 50 feet and with gradients between 2% and 8% that are moderately confined by alluvial terraces, glacial terraces or valley walls that often create a well-defined break in slope.

(ii) <u>Unconfined streams defined</u>. As used in this definition, "unconfined streams" are 2nd to 4th order Type F or S waters with bankfull widths of less than 50 feet which usually have a gradient of less than 4% (but occasionally have a gradient of up to 8%.) These streams are often located in broader headwater or tributary valleys or are flowing across the terraces of larger river valleys. They may also occur in areas where a significant change in channel slope or confinement causes high amounts of sediment deposition such as at alluvial fans or the mouth of confined tributary valleys. Channel movement typically occurs during floods when woody debris or large sediment accumulations can cause the stream or portions of the stream to jump or avulse into side channels. These side-channels are considered part of the active channel. Localized reaches of meandering or braided streams may also be present.

(iii) Unconfined meandering streams defined. As used in this definition, "unconfined meandering streams" are 5th order and larger Type S waters with bankfull widths greater than 50 feet and gradients of less than 2% with the following additional characteristics: The waters are sinuous, primarily single-thread channels that have a distinct meandering pattern readily observable on aerial photographs. Remnant side-channels and oxbow lakes often create wetland complexes within the associated channel migration zone. A diverse set of vegetation can grow within the associated channel migration zone including cedar, spruce, hardwoods, and wetland vegetation on wetter sites and Douglas-fir, spruce, hemlock and true firs on drier terraces. "Unconfined meandering streams" do not include any waters that are unconfined braided streams or unconfined avulsing streams.

(iv) Unconfined braided streams defined. As used in this definition, "unconfined braided streams" means 5th order or larger Type S waters with bankfull widths greater than 50 feet and gradients of less than 2% with the following additional characteristics: These waters have a high sediment supply and form numerous channels (multi-threaded) that are likely to move within the bankfull width of the stream in even small storm events. The frequent rate of channel movement means that the associated channel migration zone is typically sparsely vegetated with young hardwoods along the channel margins. Glacially-fed streams often have large sections of braided channel. "Unconfined braided streams" do not include any waters that are unconfined meandering streams or unconfined avulsing streams.

(v) Unconfined avulsing streams defined. As used in this definition, "unconfined avulsing streams" means 5th order or larger Type S waters with bankfull widths greater than 50 feet and gradients of less than 2% with the following additional characteristics: These waters are usually large dynamic river systems that in some cases have had dikes and levees constructed that may restrict channel movement. Numerous side channels, wall-based channels, oxbow lakes, and wetland complexes may exist within the associated channel migration zone. Sizeable islands with productive forest land may also exist within the zone. Woody debris jams with larger diameter pieces of large woody debris are an important element for creating pools within these waters, as well as redirecting flow to create side channels and islands. Vegetation within the associated channel migration zone can include cedar, spruce, hardwoods, and wetland vegetation on wetter sites and Douglas-fir, spruce, hemlock and true firs on drier terraces or islands. "Unconfined avulsing streams" do not include any waters that are unconfined meandering streams or unconfined braided streams.

(vi) CMZ for moderately confined streams. The channel migration zone for moderately confined streams is determined by reference to the surrounding topography and vegetation. The zone typically ends at a well-defined break in slope created by alluvial terraces, glacial terraces or valley walls. Vegetation within the channel migration zone is usually dominated by young hardwoods (alder and cottonwood) because of the high frequency of disturbance from channel movement, floods, or dam-break floods. Wet areas and seeps with vegetation such as devil's club and salmonberry are frequently found, particularly at tributary junctions. Portions of the zone such as low terraces that are not disturbed as frequently can contain upland vegetation. Woody debris jams, gravel bars, and abandoned side branches are common. The ground surface within the channel migration zone usually has a layer of fine sediment, especially around vegetation, but can also have significant areas of exposed gravel and cobble. The area outside of the zone usually has deeper soils that can support conifer and other upland plant species. One rule of thumb to help locate the elevational extent of the channel migration zone is to measure the distance that is twice the reach-averaged bankfull depth. The channel migration width is usually less than four channel widths across. For example, a stream with a bankfull width of 10 feet in this situation would typically have a total channel migration zone width of less than 40 feet.

(vii) CMZ for unconfined streams. The channel migration zone for unconfined streams is likewise determined by reference to the surrounding topography and vegetation. Delineating the boundaries of these zones can be more difficult because of the subtle changes in the surrounding topography and vegetation. A diverse set of vegetation can grow within these zones including cedar, spruce, hardwoods, and wetland vegetation on wetter sites and Douglas-fir, spruce, hemlock and true firs on drier terraces. The extent of the channel migration zones often coincide with the furthest extent of the side-channels. A side-channel may currently be considered a fish-bearing water or it may be a recently abandoned channel as evidenced by the presence of a swale with exposed gravel and cobble, woody debris jams or signs of recent disturbance. The entire channel migration zone width is typically on the order of 10's of feet for small streams, but can be a few hundred feet on moderate-sized streams.

(viii) CMZ for unconfined meandering streams. The channel migration zone for unconfined meandering streams can be determined using one of the two following options: Option 1 defines the channel migration zone as the area between two generally parallel lines representing the amplitude of the meander wavelength as determined from maps or aerial photographs. An example of the application of this Option is attached as Schedule A-3. Option 2 defines the channel migration zone as the annual average rate of bank erosion at meander bends for the reach of stream that exhibits meandering behavior multiplied by the years required to grow functional size large woody debris. An example of the application of this Option is attached as Schedule A-4. As used in this definition "functional large woody debris" means woody debris with a diameter of at least 0.5 of the reach average bankfull depth. The intent of Option 2 is to allow a more accurate representation of the area subject to channel migration using site-specific characteristics. Option 2 will require more expertise to define the channel migration zone because an analysis of the long-term meander rate and reach-averaged bankfull depth needs to be conducted. Option 1 provides a more easily implemented rough approximation of the boundaries of the zone, particularly in cases with multiple ownerships. The Board Manual field guide will provide further guidance on delineating the amplitude of the meander wavelength for Option 1 and determining average meander rates for Option 2. The total channel migration zone width will typically be a few hundred feet.

(ix) CMZ for unconfined braided streams. The channel migration zone for unconfined braided streams is the same size as the bankfull width of such streams although this often represents a large proportion of, or even the entire, valley floor. The width of the channel migration zone for these streams is usually a few hundred feet.

(x) CMZ for unconfined avulsing streams. The channel migration zone for unconfined avulsing streams can include much of the valley bottom and is typically hundreds of feet, but can easily be a few thousand feet, in width. Delineation of the boundaries is often determined based upon a review of the associated vegetation and history of past migration.

(xi) Levees. The channel migration zone of any stream determined pursuant to the preceding subparagraphs may be further limited to exclude the area behind a permanent dike or levee provided such permanent dike or levee was constructed pursuant to appropriate federal, state, and local requirements. As used in this subparagraph, a "permanent dike or levee" is a channel limiting structure that either (1) is a continuous structure from valley wall or other geomorphic structure that acts as an historic or ultimate limit to lateral channel movements to valley wall or other such geomorphic structure and is constructed to a continuous elevation exceeding the 100-year flood stage (1% exceedence flow); or (2) is a structure that supports a public right-of-way or conveyance route and receives regular maintenance sufficient to maintain structural integrity; provided, however, a dike or levee shall not be considered a "permanent dike or levee" if the channel limiting structure is perforated by pipes, culverts or other drainage structures that allow for the passage of any life stage of anadromous fish and the area behind the dike or levee is below the 100 year flood level.